From the Universe to the focal plane

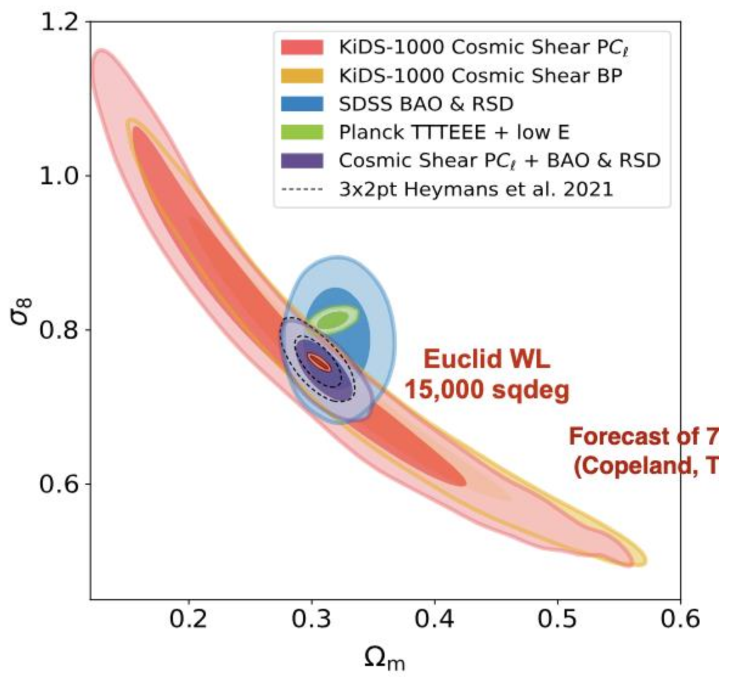
Data acquisition challenges of galaxy surveys

Understanding the LSS

INTRODUCTION

The observed Universe

Cosmology



e.g. see lecture by Elisabeth Krause, Cora Uhlemann

This lecture

This lecture

The observed Universe

Optical and NIR
galaxy surveys

Emphasis on Euclid VIS

Astronomical
foreground

Optical
system

Detector

Telescope

Processed
data

Galaxy
catalogues

Cosmology

Why as a theorist should you be interested in challenges of data acquisition?

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$$w(z) = w_0 + w_a \frac{z}{1+z}$$

$w(z) = 0.95 \pm 0.05$ is not interesting

$w(z) = 0.95 \pm 0.01$ is interesting

Slide inspired from A. Taylor

Why as a theorist should you be interested in challenges of data acquisition? Example of Weak Lensing

- We measure cosmological parameters from the shear power in tomographic redshift slices. With stage-IV Dark Energy surveys (e.g Euclid): accuracy of $\sigma(w_0) = 0.01$ and $\sigma(w_a) = 0.1$

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- The error on w scales roughly as $\frac{\Delta w}{w} \approx 10 \frac{\Delta\gamma}{\gamma}$.

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- **Statistical** precision set by $\frac{\Delta \gamma}{\gamma} \approx \frac{\sigma_e}{\gamma\sqrt{N}}$ where $\sigma_e \approx 0.3$ is the shape noise. So we need $N = 10^9$ galaxies. Huge survey!

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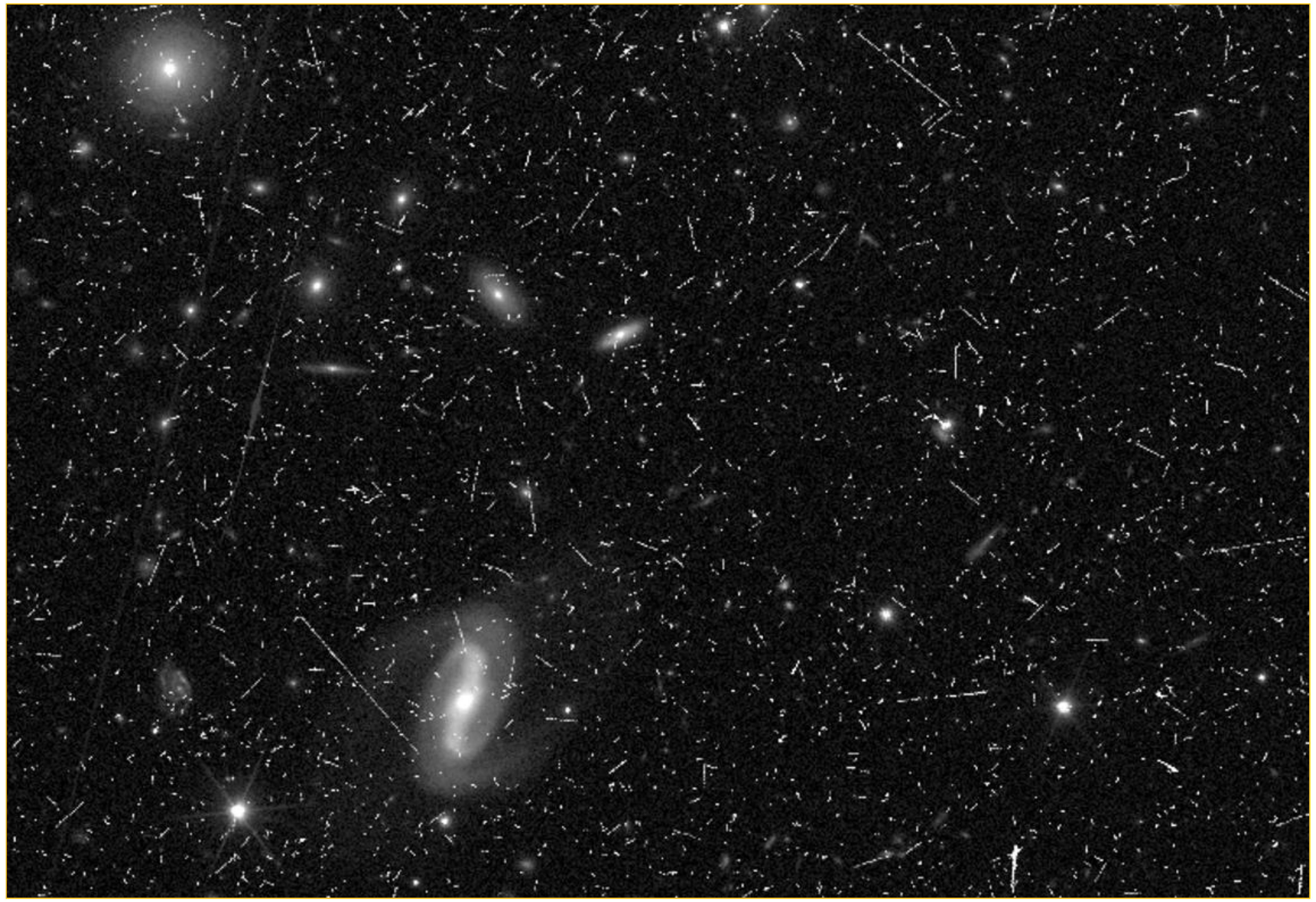
- Error budget will be dominated by systematics: we want to control with high precision optics and electronics and data processing.

Slide inspired from A. Taylor

Why as a theorist should you be interested in challenges of data acquisition? Example of Weak Lensing

A raw Euclid VIS image



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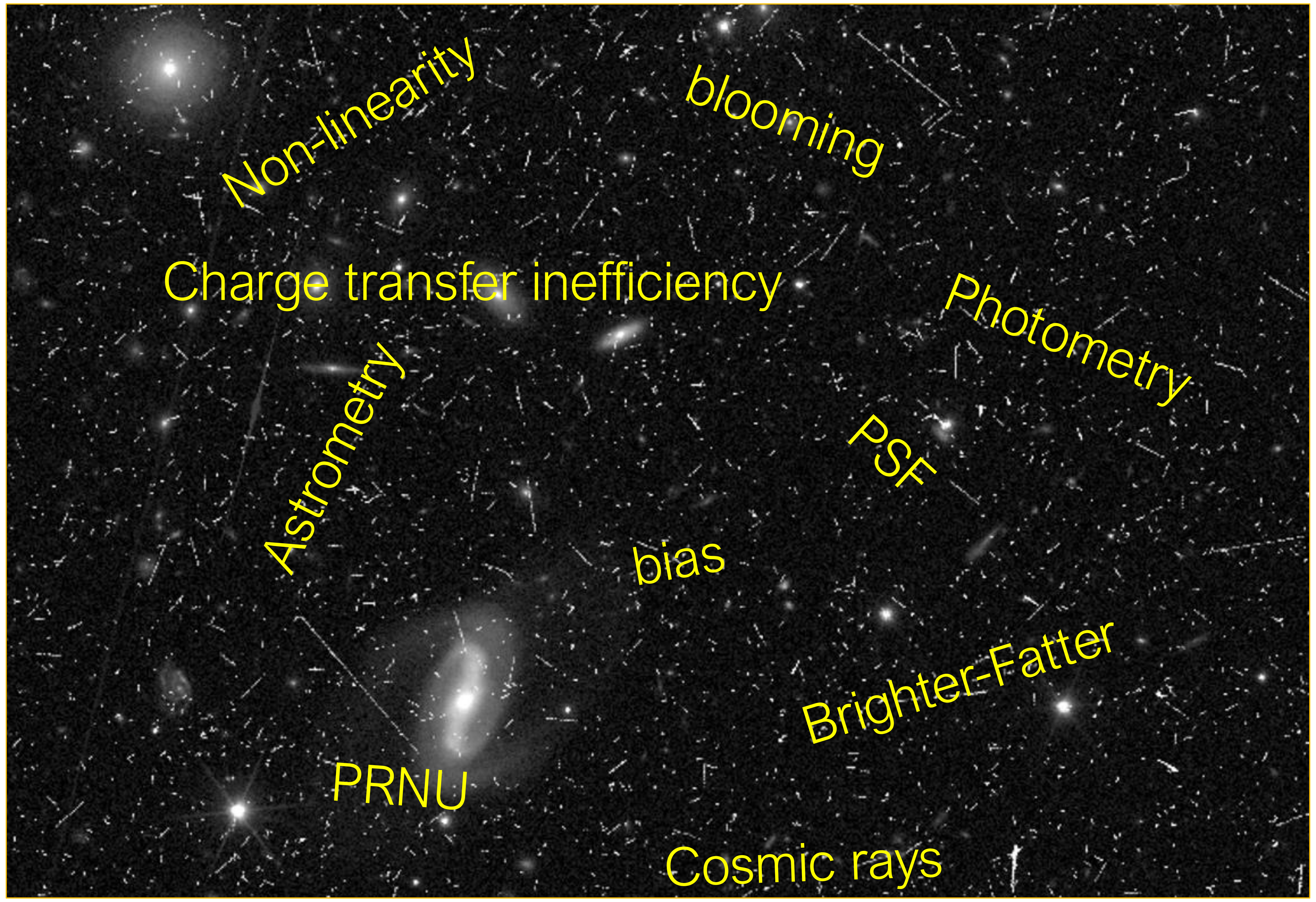

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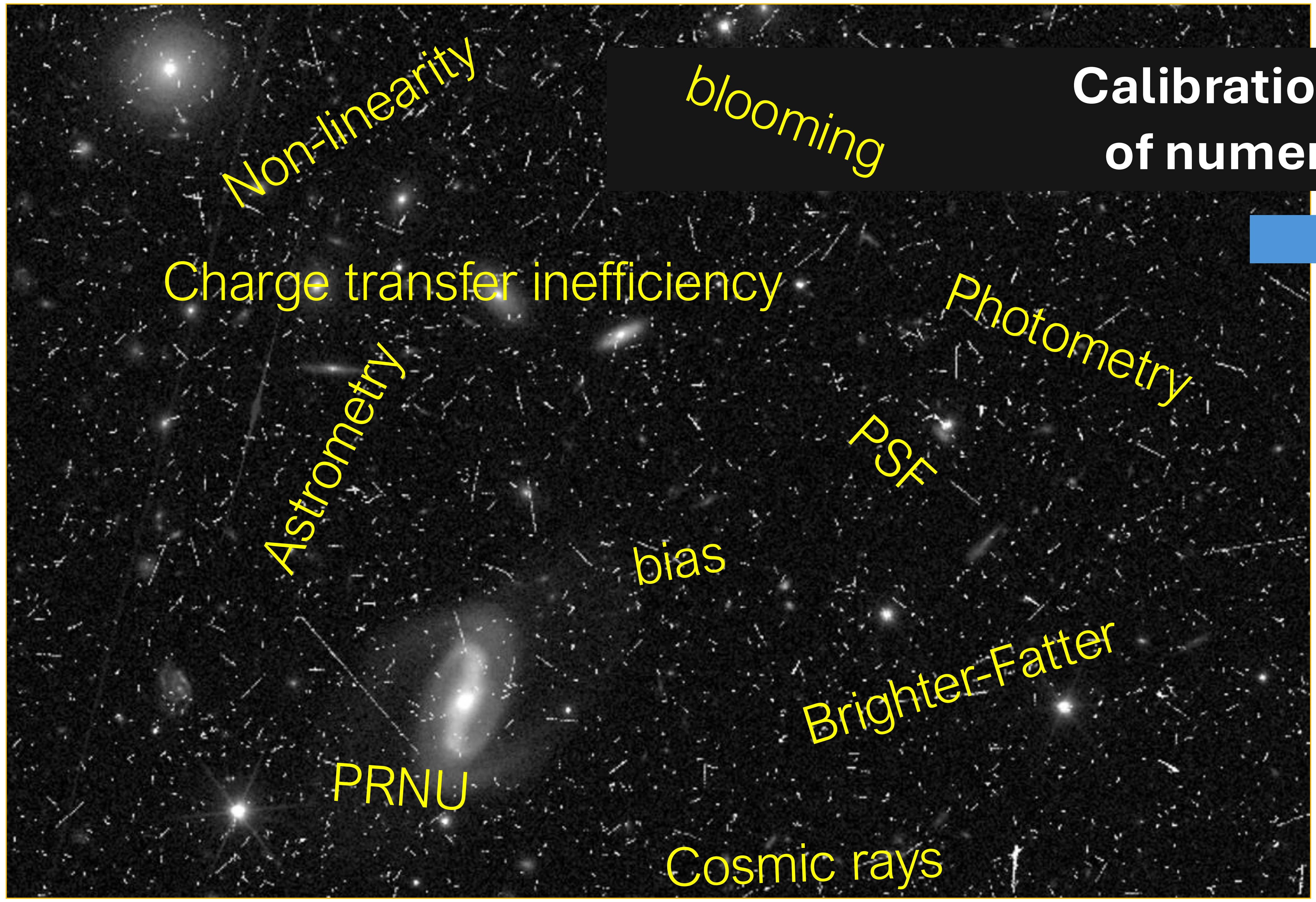
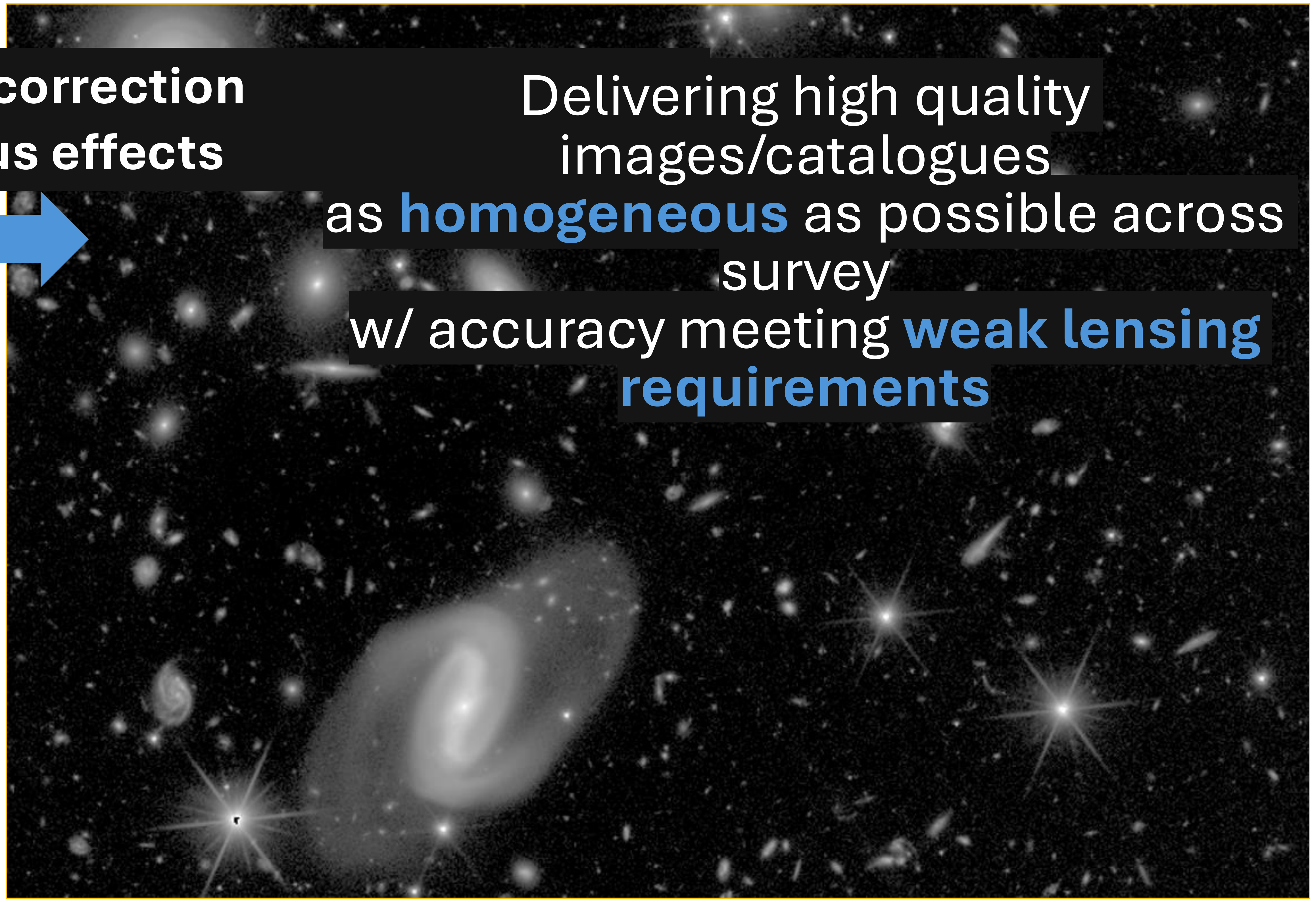


Calibration/correction of numerous effects



Delivering high quality images/catalogues as **homogeneous** as possible across survey w/ accuracy meeting **weak lensing requirements**

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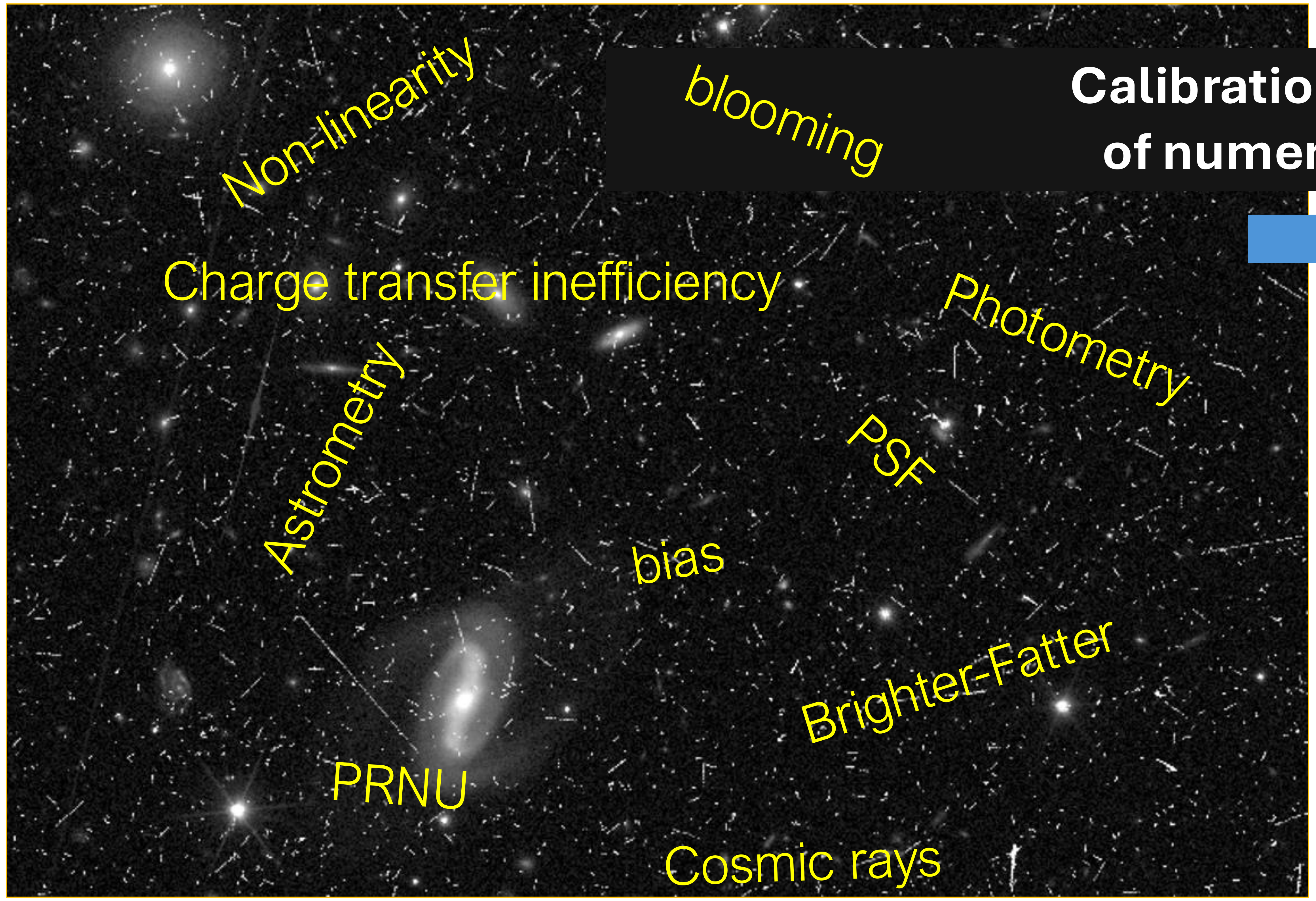

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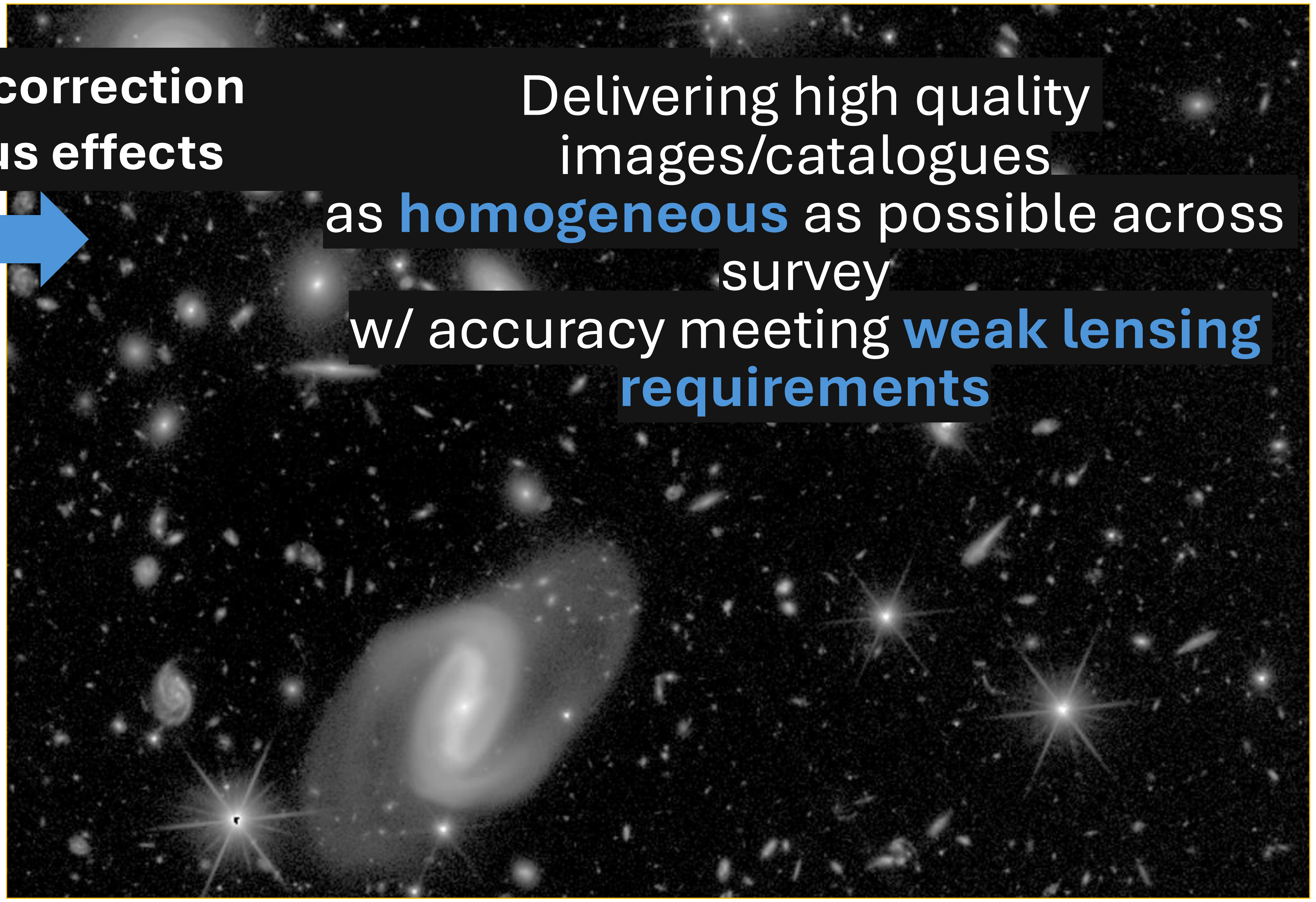


What is hard

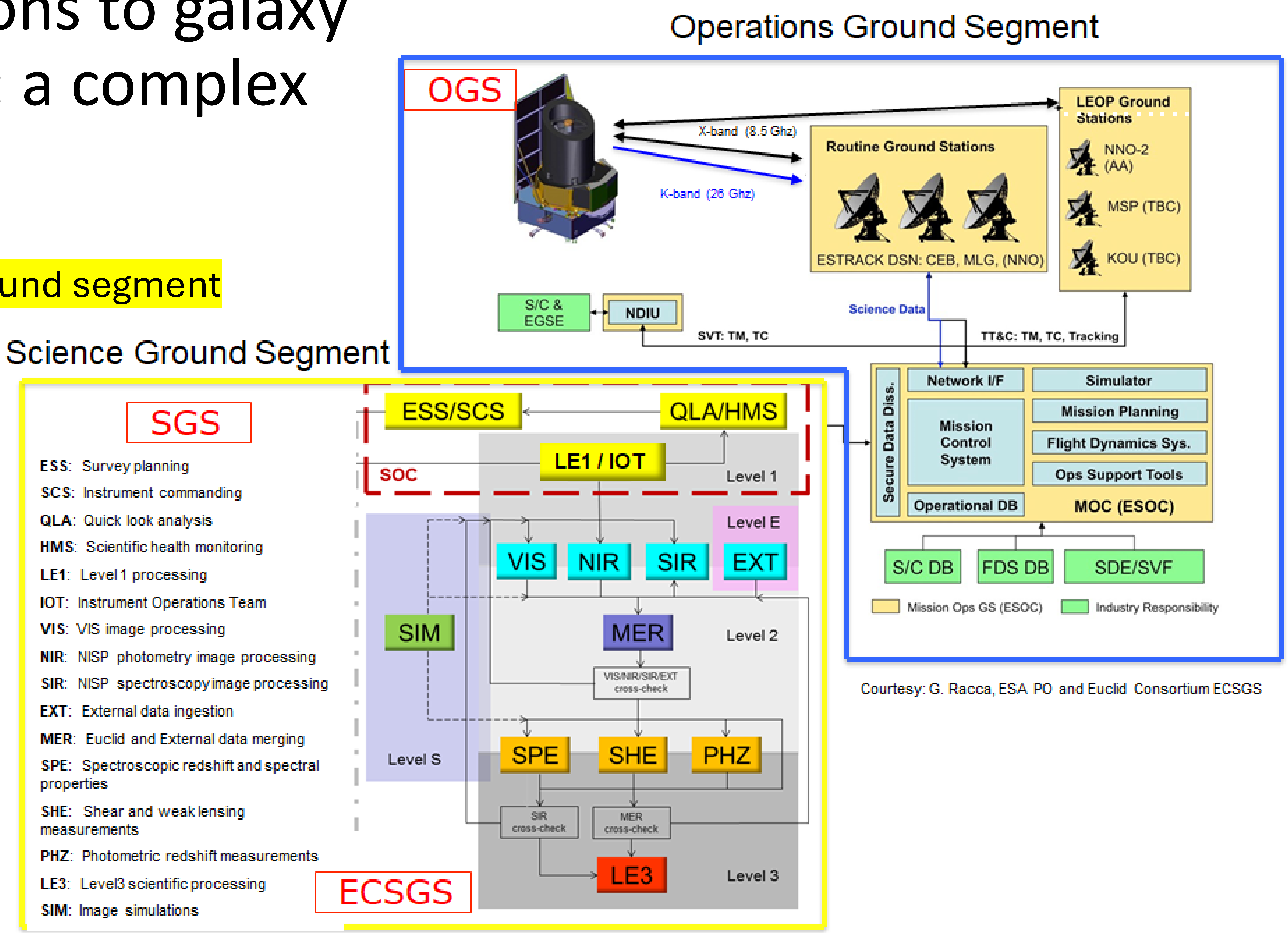
- Several effects are **interrelated** (CTI/NL/BFE);
- Significant **time evolution** of some effects (ice);
- Some **unexpected** events (proton shower, etc.)

Why as a theorist should you be interested in challenges of data acquisition? Example of Weak Lensing

- Possible biases comes from many sources, so each need to be controlled to even higher precisions.
- At small scale, baryonic physics impact shear measurement, so we want to measure shear at scale larger than a few arcmin. We must pay attention to detection effects that could cause systematics coherent distortion at these scales
- If there are systematic residuals impacting shear measurements, we will misinterpret the result and wrongly estimate the cosmological parameters
- Engineers cannot do everything by themselves: they need input from researchers to understand what to precisely monitor and how the residuals of their correction impact shear estimation.

From photons to galaxy catalogues: a complex chain

Example of
Euclid science ground segment



Courtesy: G. Racca, ESA PO and Euclid Consortium ECSGS

Courtesy Euclid Consortium/ESA/SGS Team.

From photons to galaxy catalogues

- A very complex chain
- A huge group of persons that must work together: technicians, software engineers, research engineers, astronomers
- In any case, **very inter-disciplinary** work:
  - Cosmology
  - Astrophysics: space weather, astronomical foreground, etc.
  - Detector physics
  - Optics: filters, dichroic, grism, ray tracing
  - Engineering
  - Software / pipelines / algorithms
  - Requirement flow-down / interfaces / management / communication

It’s fascinating and fun!

Outline

~~Introduction~~

1. Designing a galaxy survey: basic considerations on telescopes

Telescopes in comparison, on-ground or in space, fov/resolution/sensitivity, imaging versus spectroscopy

2. Overview of existing and upcoming galaxy large-surveys

Overview of DE surveys, Spectroscopic surveys. Zoom on DESI and follow-up, Photometric surveys. Zoom on Euclid

3. From distant galaxies to the detector: the case of VIS on Euclid

Astronomical foreground, being in space, data acquisition chain, zoom on BFE and CTI

4. Euclid: the adventure of a space telescope

Some surprises that can happen when you launch at L2

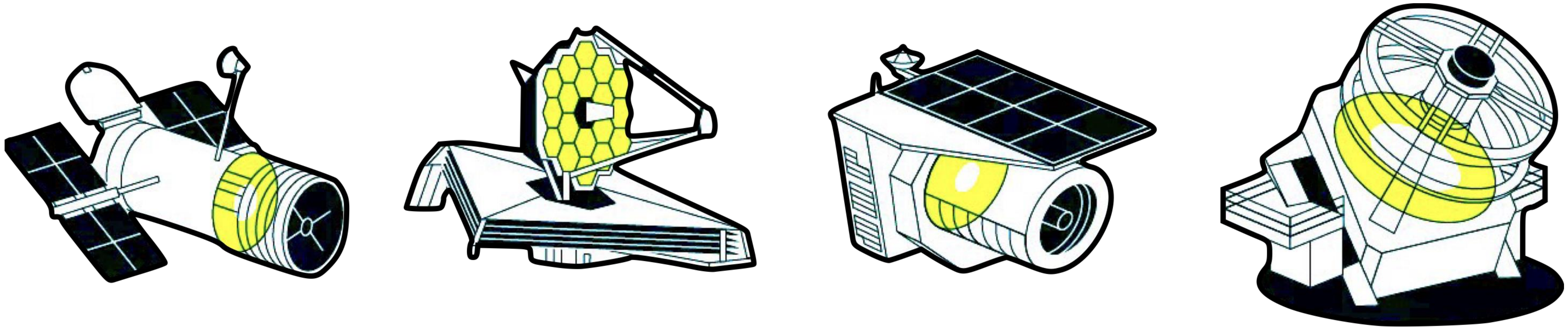
Conclusion

1. Designing a survey

Some basic considerations on telescopes

Telescopes in comparison

- Each telescope has its own “specialty” on which depends mirror size + focal plane area + detector sensitivity + strategy of sky scanning



https://www.mpg.de/24878805/telescopes-in-comparison?c=2249

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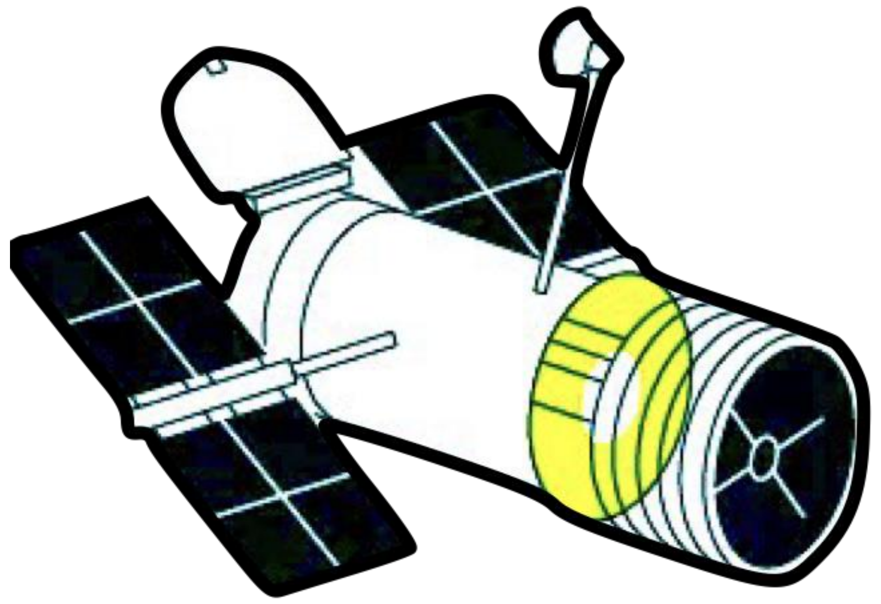
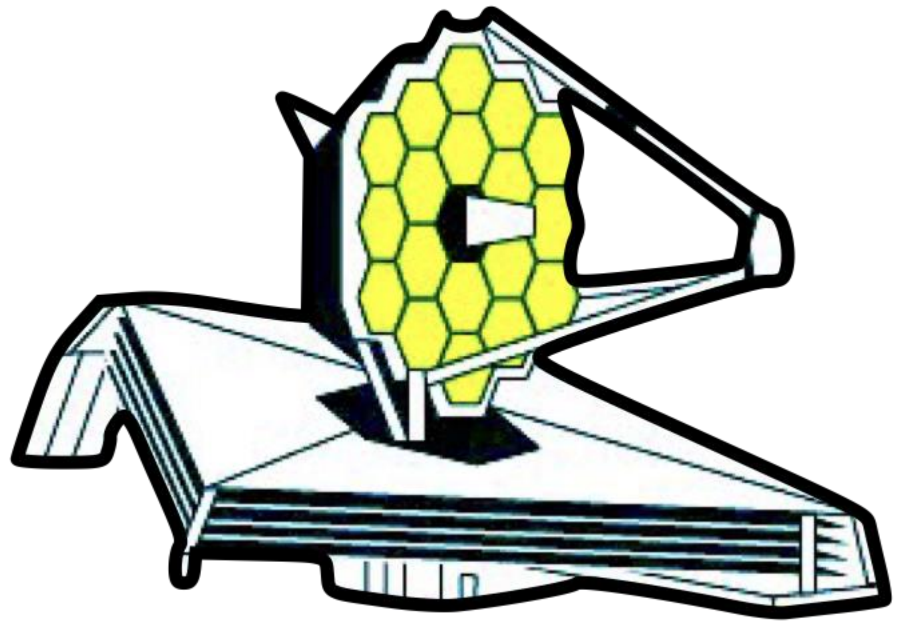
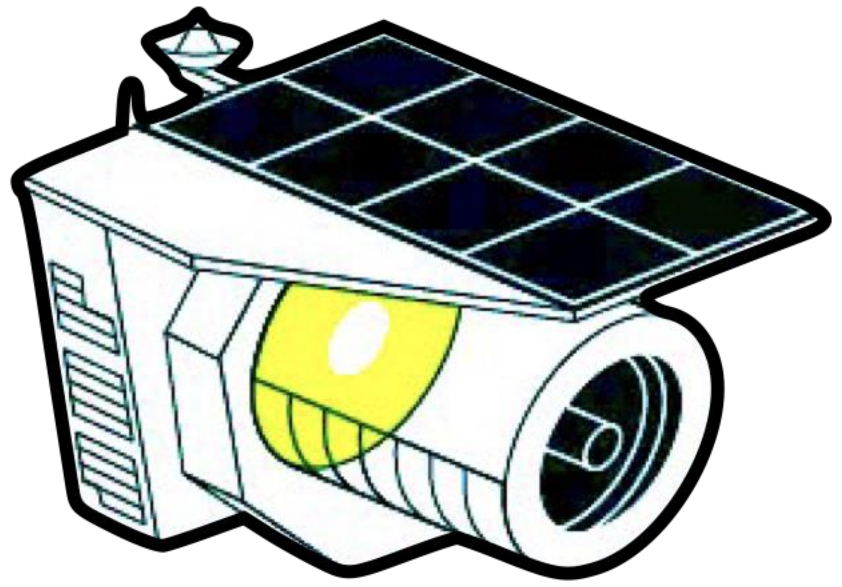


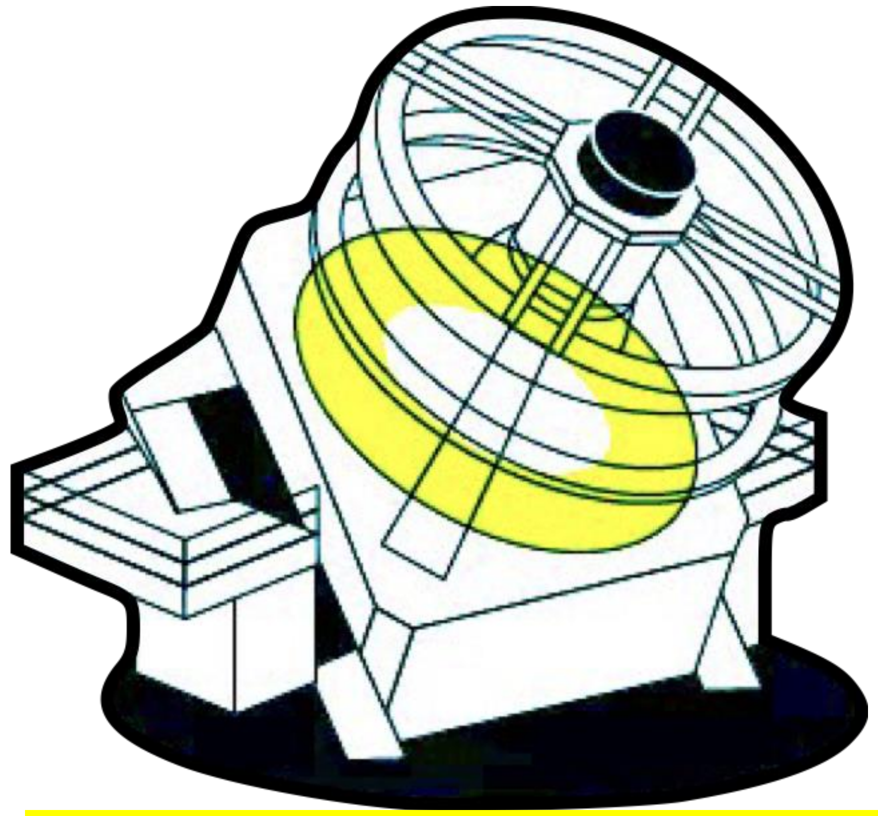
HST
Launch: 1990



JWST
Launch: 25 /12/2021



Euclid
Launch: 1 /07/2023



Vera Rubin Observatory
First light: 06/2025

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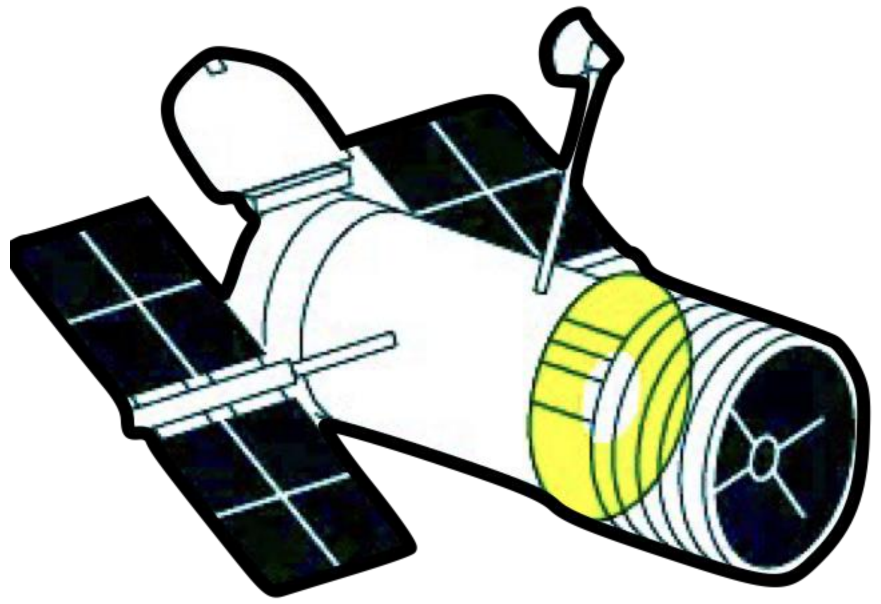
On-ground or in space?

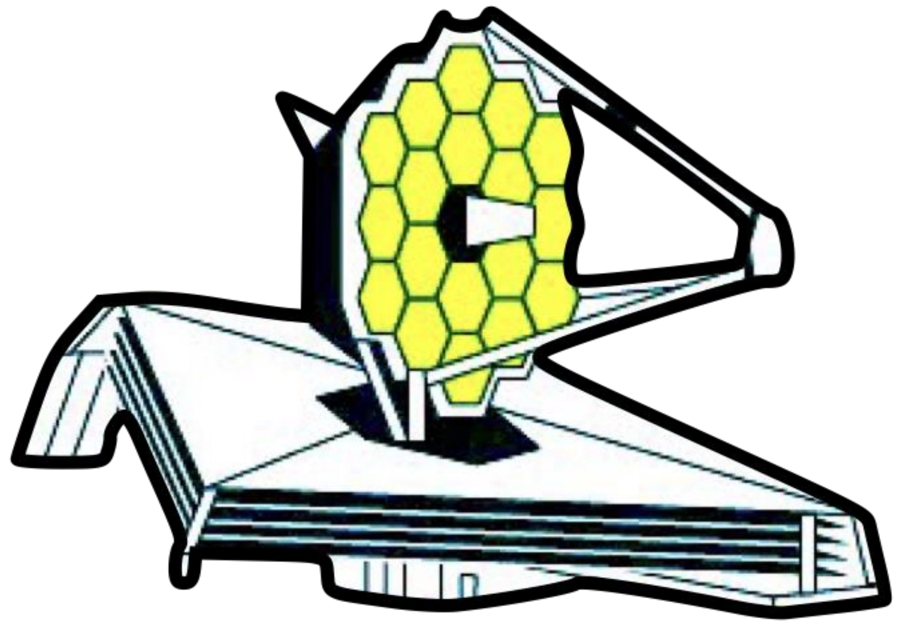
- Each telescope has its own "specialty" on which depends mirror size + focal plane area + detector sensitivity + strategy of sky scanning
- Data from **ground-based** telescopes are affected by **atmosphere** which filters certain wavelengths + "low" seeing quality

Low orbit (~515km)
0.075" at ~700nm



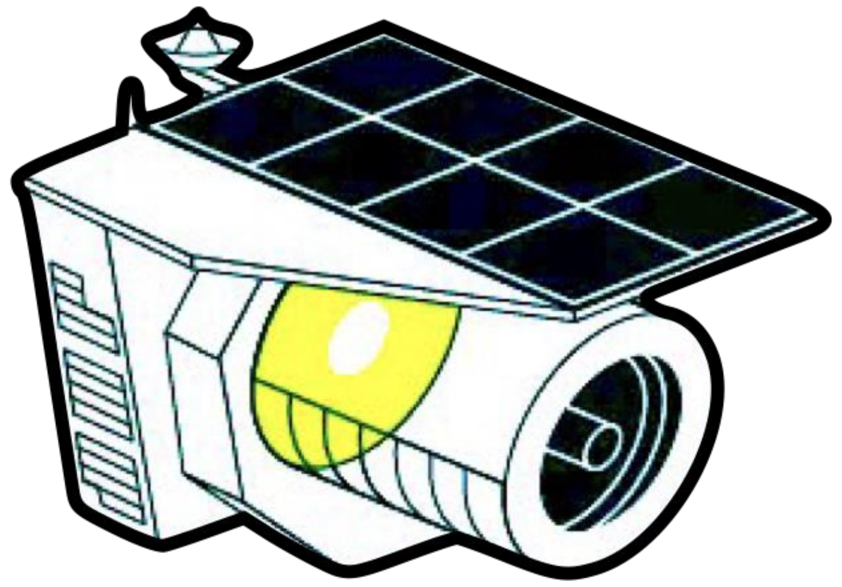
HST
Launch: 1990

L2
0.023" at ~700nm



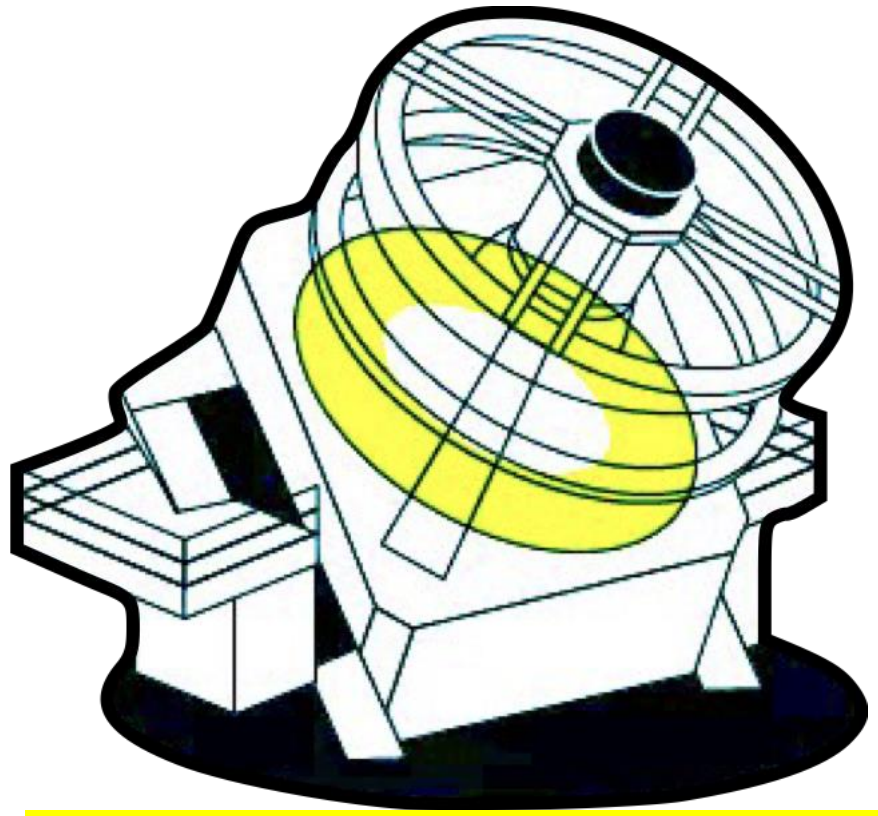
JWST
Launch: 25 /12/2021

L2
0.16" at ~700nm



Euclid
Launch: 1 /07/2023

Chile
0.67" at ~700nm



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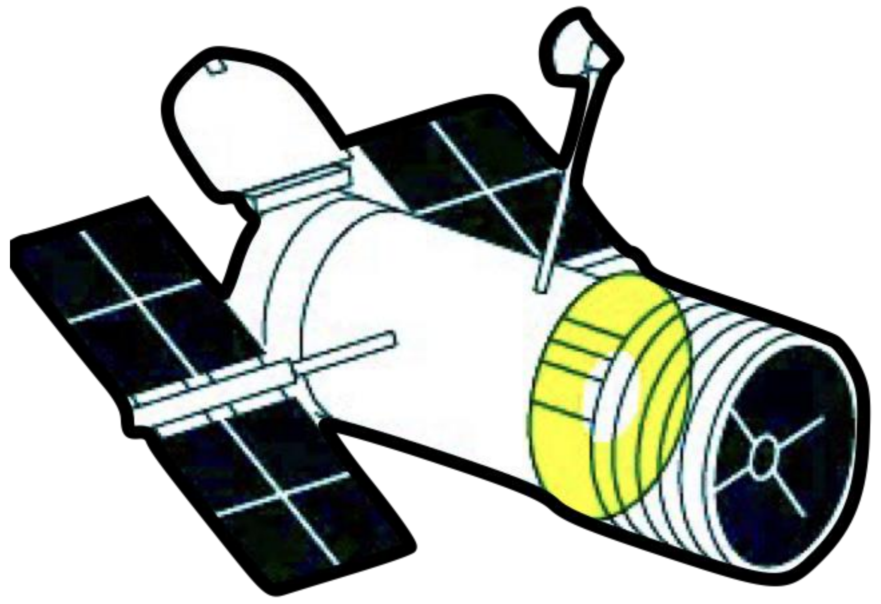
- **On-ground** telescopes can host **larger mirror** and **larger camera** than space telescopes



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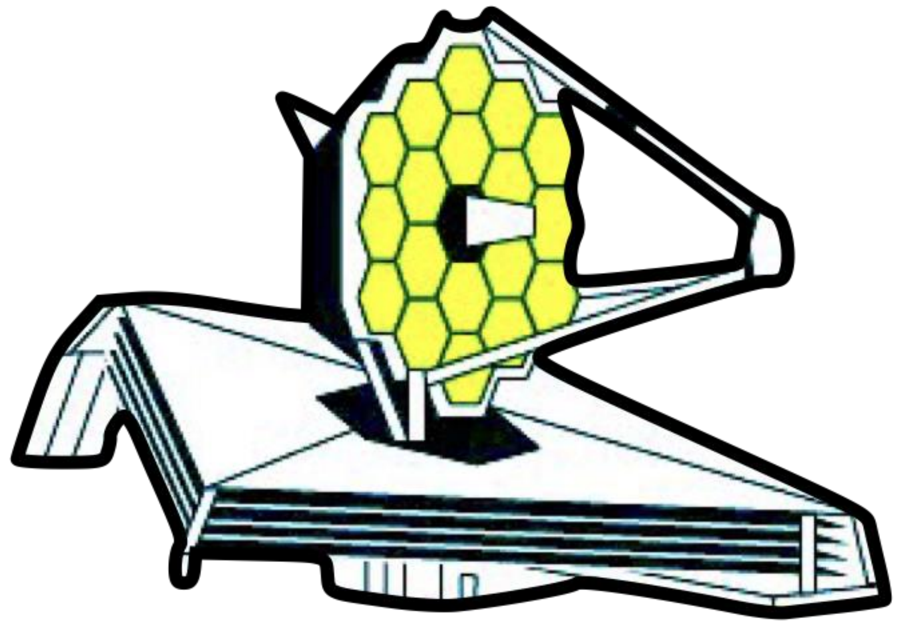

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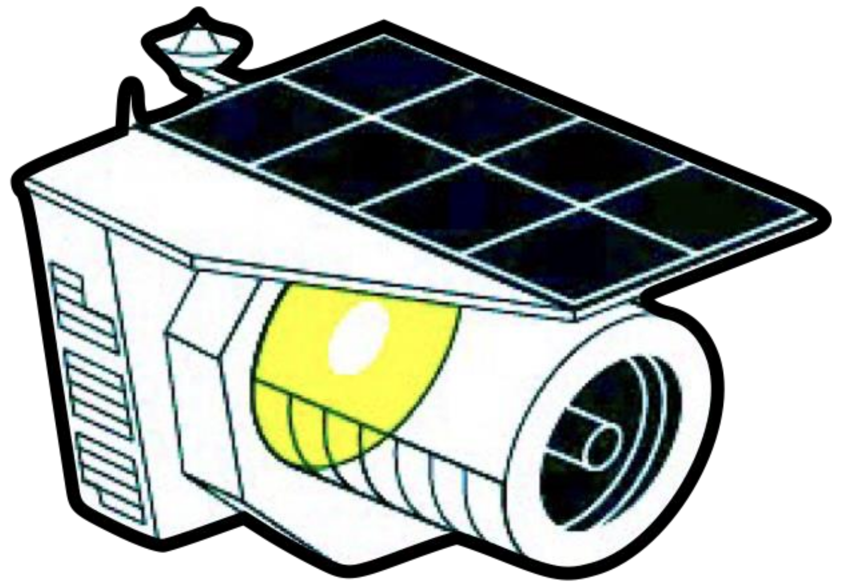

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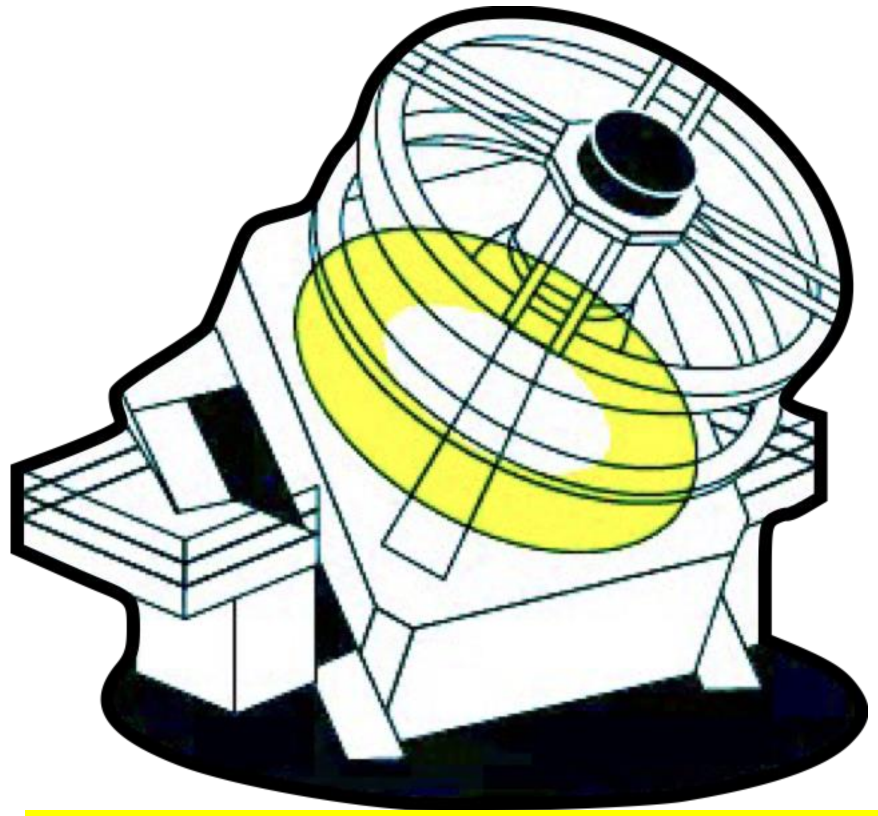

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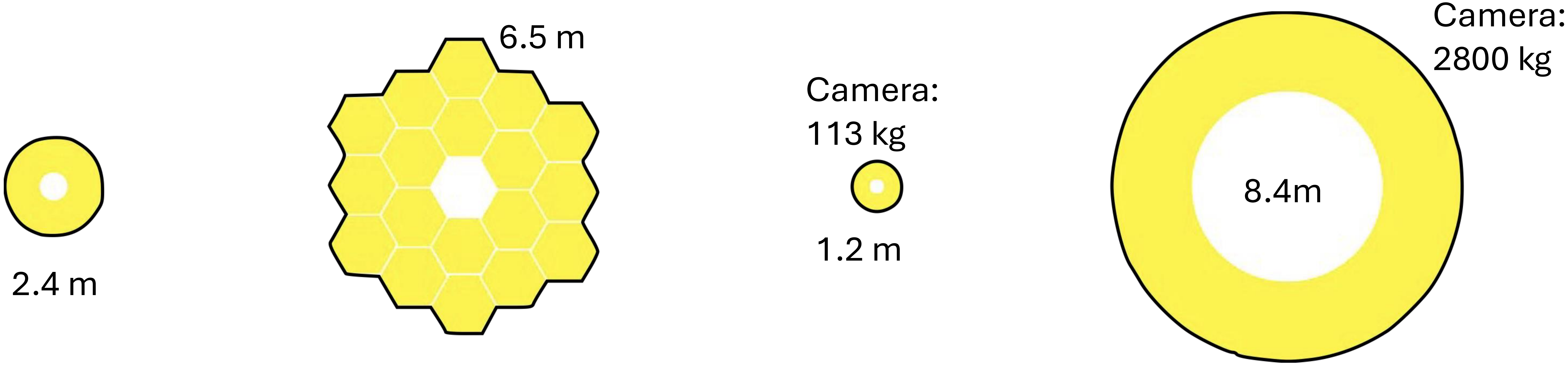

HST
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Euclid
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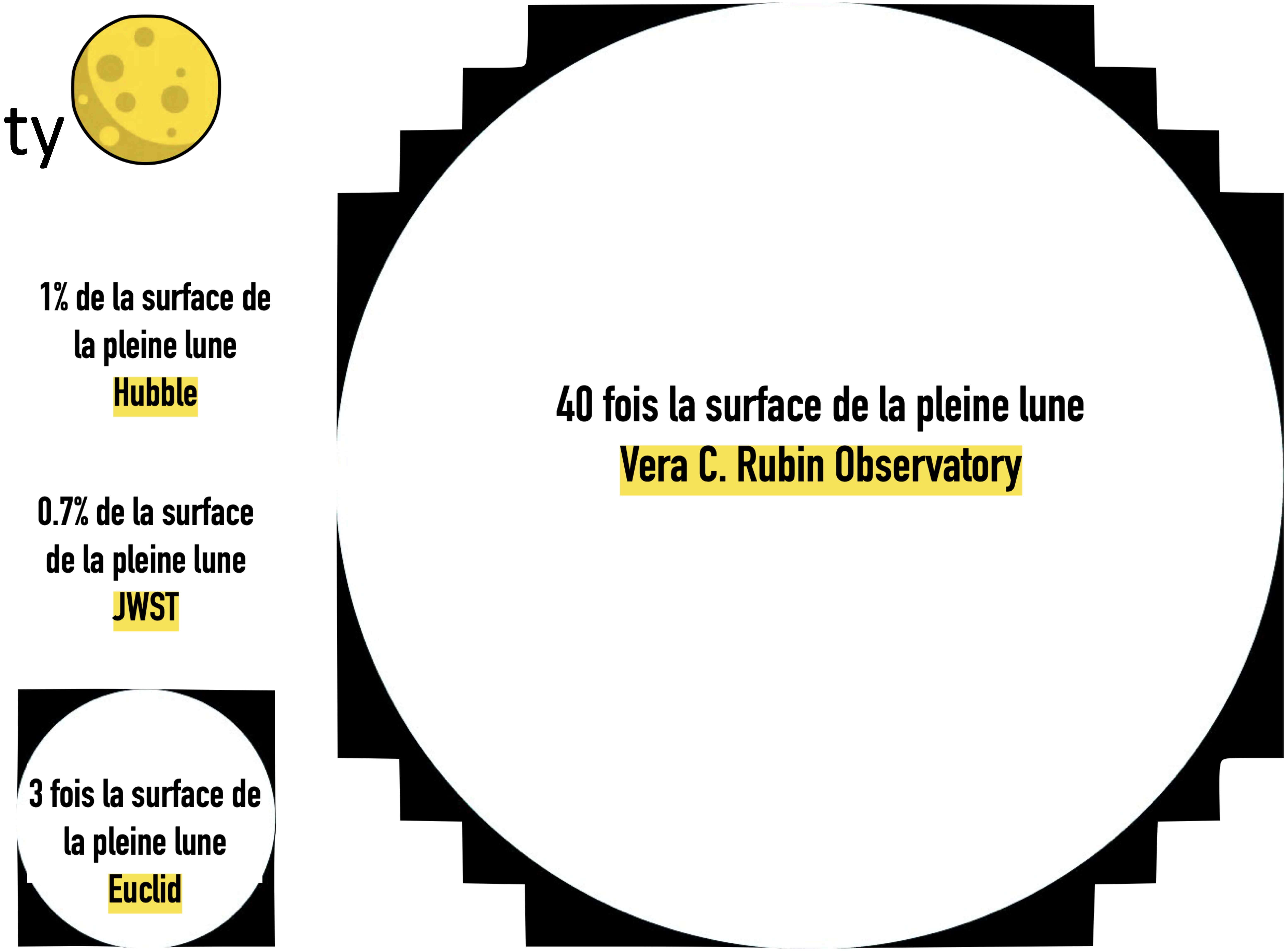
https://www.mpg.de/24878805/telescopes-in-comparison?c=2249

Field of view / resolution / Sensitivity

- **Sensitivity** depends on:
  - mirror size
  - sensitivity of the detector
- **Spatial resolution** depends on:
  - Atmospheric turbulence
  - mirror size size and wavelength. Rayleigh Criterion: $R \sim 1.22 \frac{\lambda}{D}$
- Field of view depends on
  - detector size



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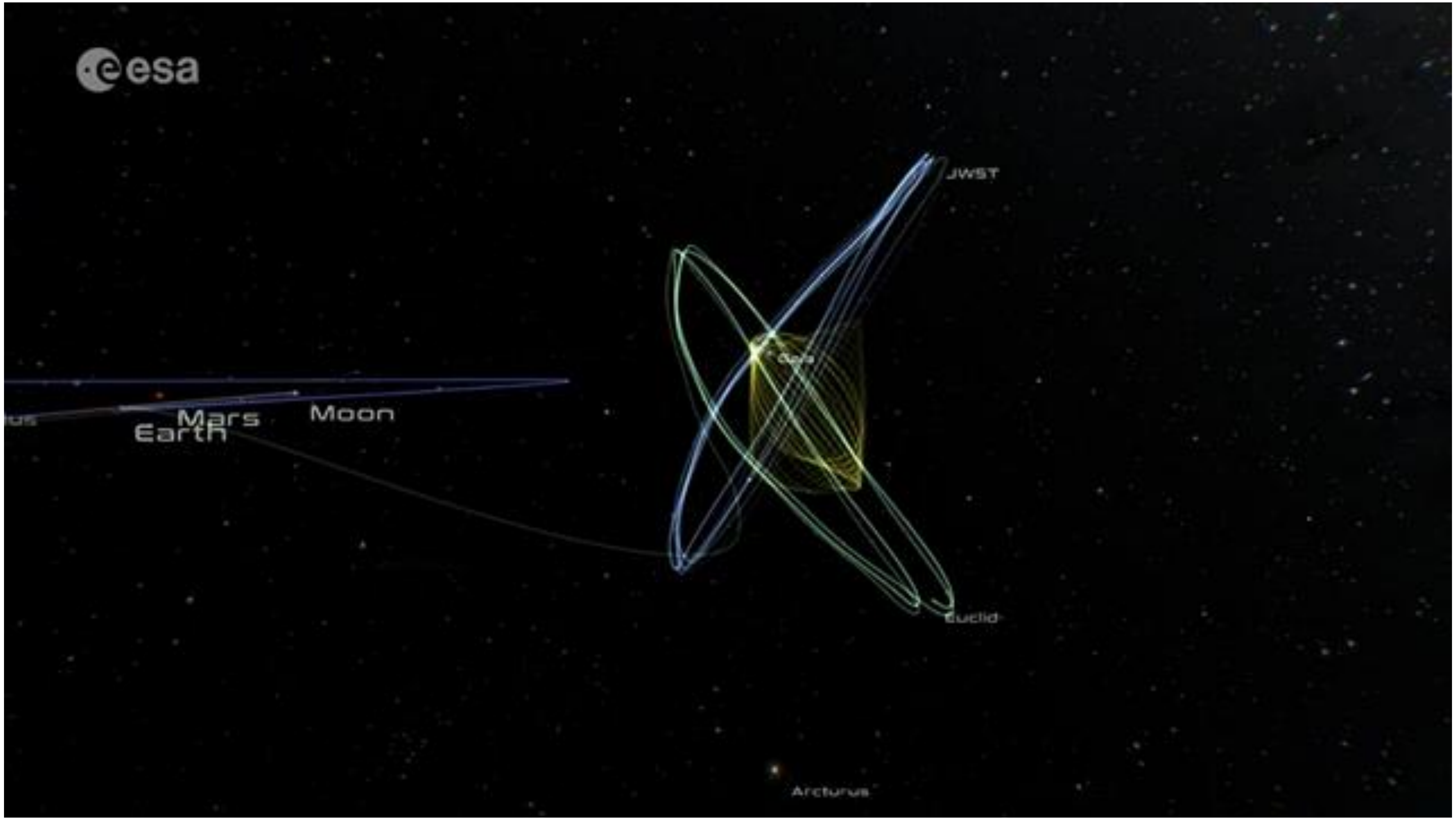
In space: low-orbit or L2?



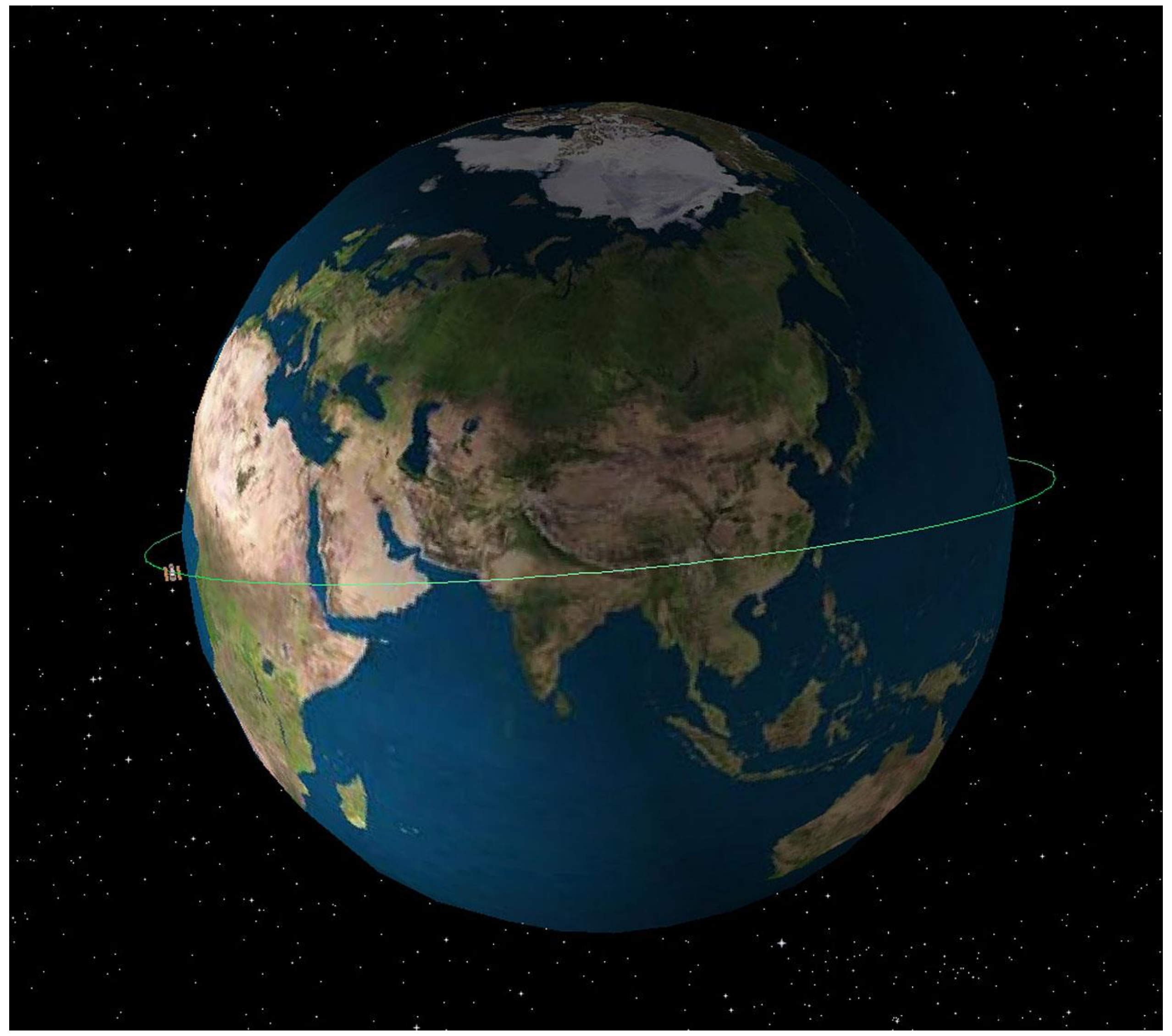
In space: low-orbit or L2?

- **Low-orbit: e.g. HST (< 600km)**
  - Maintenance is possible!

BUT

  - Target occultation by the Earth for varying duration during each 96-minute orbit, depending on target's angle from the spacecraft's orbital plane
  - Geocoronal emission, Earth shine, zodiacal light
  - Orbital thermo-cycling / shadow passage every 90 min

Credit: NASA & ESA



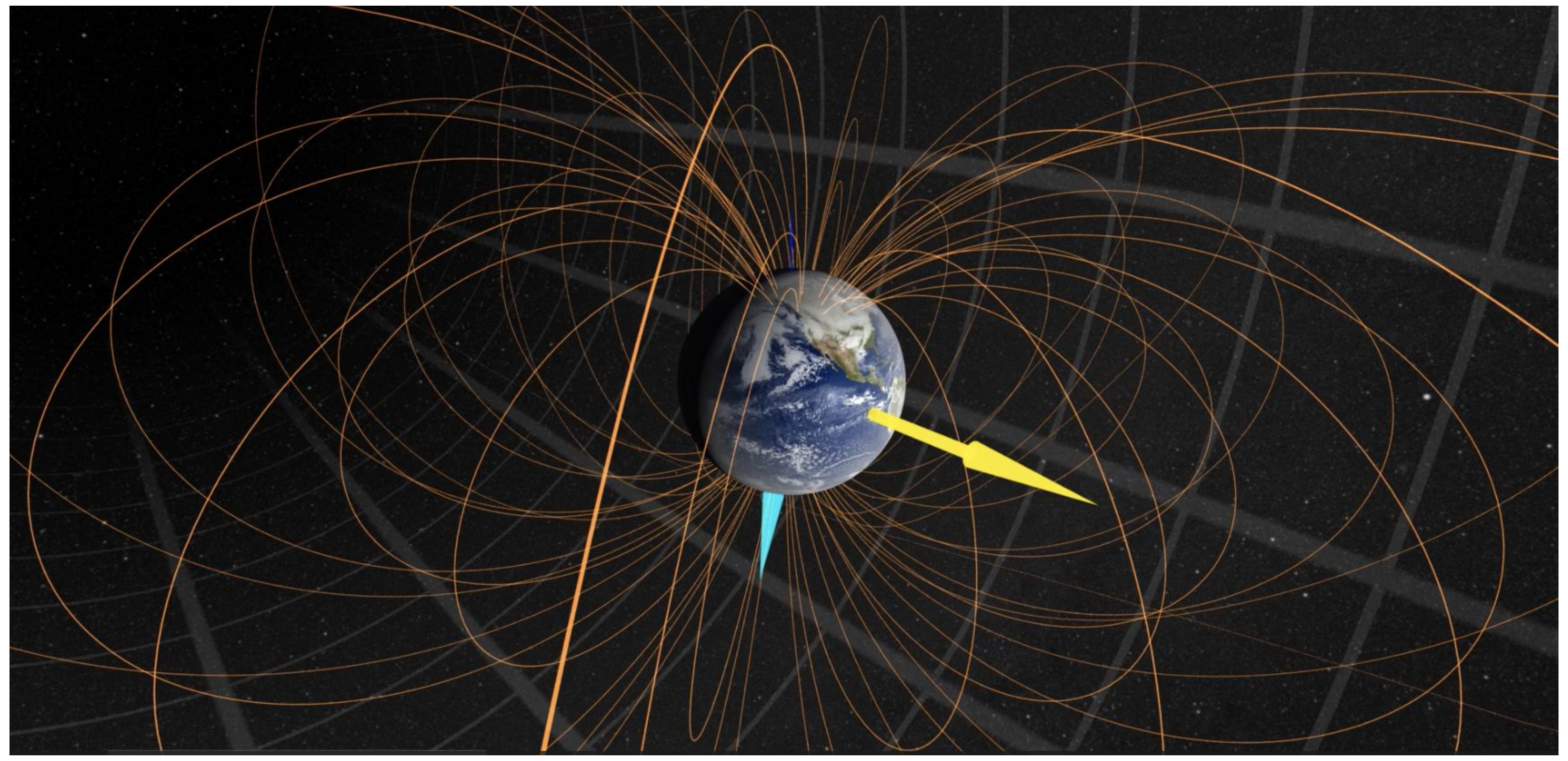
https://hst-docs.stsci.edu/hsp/the-hubble-space-telescope-primer-for-cycle-33/hst-primer-orbital-constraints

- **L2: e.g. JWST, Euclid, Gaia, Planck, ...etc**
  - Lower background
  - More thermally stable
  - Better visibility all the time.

BUT

  - No possible maintenance
  - More sensitive to space weather (not protected by earth magnetic field)

Credit: NASA's Scientific Visualization Studio



Earth magnetic field

2. Existing and upcoming galaxy large-surveys for DE

A. Spectroscopic redshift surveys
B. Weak lensing surveys

Imaging

Weak lensing

- Photometric surveys:
  - galaxy angular positions
  - shapes
  - redshift distributions in tomographic bins

➢ shear power in tomographic redshift slices

- Sources of noise:
  - Not enough statistics
  - Redshift distribution incorrectly known
  - Systematics in shape measurements

- Strategy to improve measurements:
  - **Larger sky coverage, deeper images**
  - **Multi-wavelength photometry** + good knowledge of galaxy spectra diversity
  - **High resolution** photometry (in space), NIR, good control of the wavefront error

Imaging versus spectroscopy

Weak lensing clustering

- Photometric surveys:
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  - shapes
  - redshift distributions in tomographic bins

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- Spectroscopic surveys:
  - galaxy angular positions
  - accurate redshifts. In general target selections from imaging surveys (not for grism)

➢ Compress galaxy positions into power spectrum

- Sources of noise:
  - Not enough statistics
  - redshift errors
  - Finite number of tracers / sampling bias

- Strategy to improve measurements:
  - **Larger sky coverage, fainter flux limit** (less catastrophic failures, higher sampling)
  - **Larger wavelength coverage** (reduce sampling bias, higher redshift)
  - **Higher spectral resolution** (better quality redshift, less catastrophic failures) $R = \frac{\lambda}{\Delta\lambda}$

Additional considerations on spectroscopy

Multi-object spectrograph

e.g: BOSS, DESI

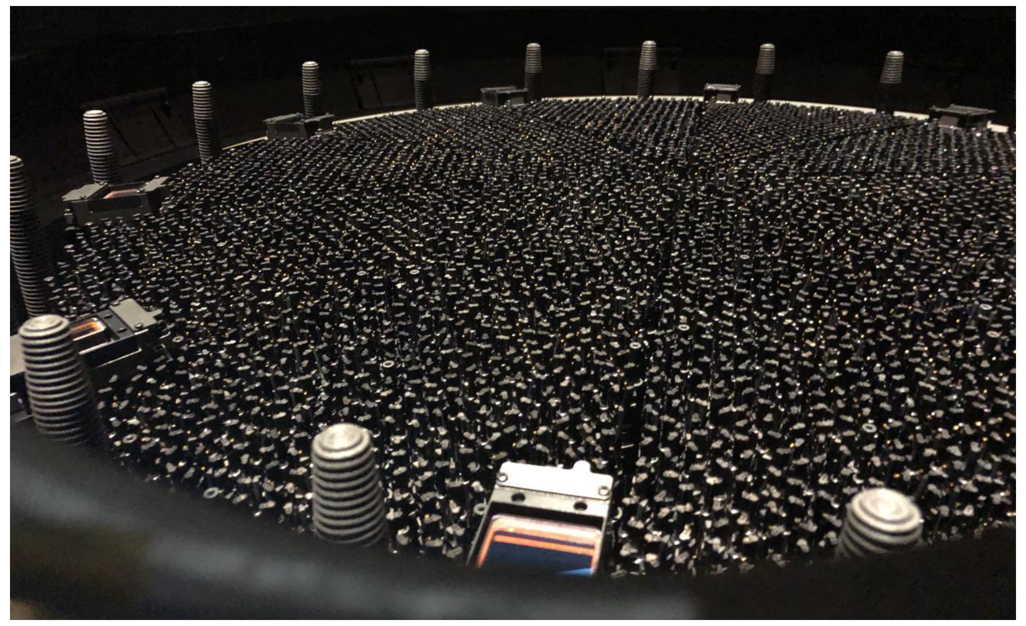
- **Need imaging survey for target selection**
- Large-flexibility in imaging strategy

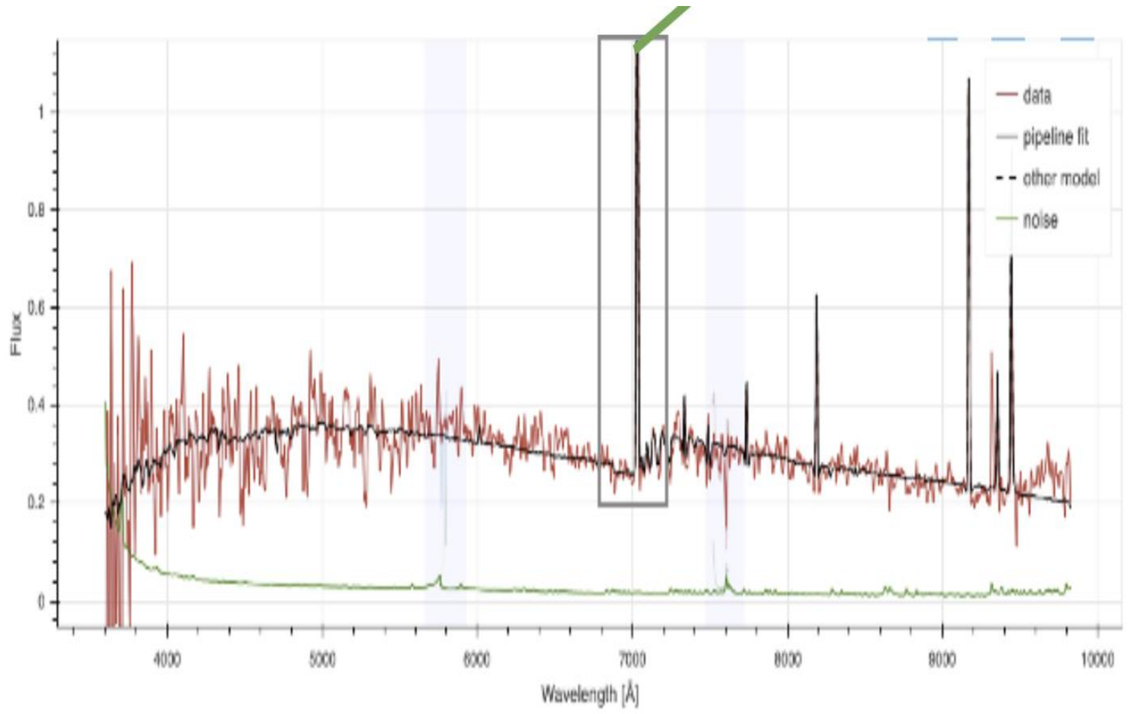
Slitless spectroscopy

e.g: NISP (Euclid), WFI (Roman)

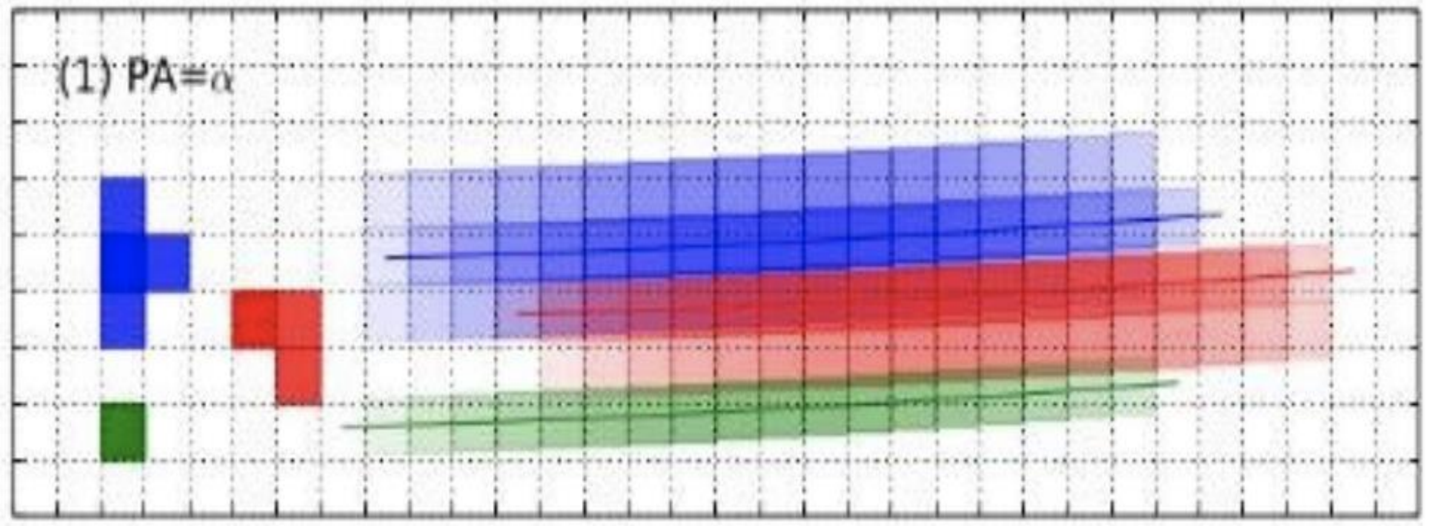
- No target selection ~ dispersed imaging
- **Intricate mixing of spatial and spectral information**

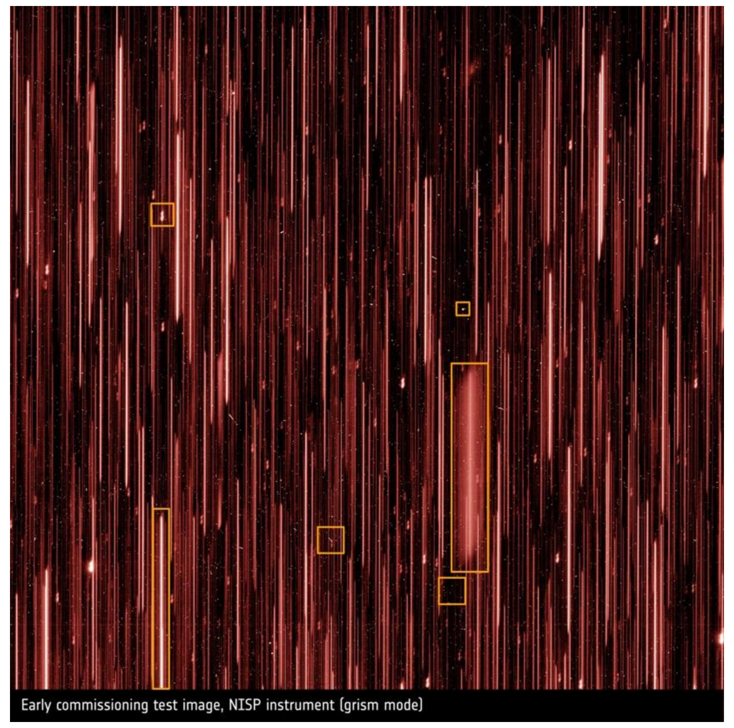
Credit: DESI collaboration





Credit : Yannick Copin





Performances: **Number of fibers (and configuration time), Wavelength resolution** (+FoV, sensitivity, wavelength range)

Performances: **Spatial resolution, Wavelength resolution** (+FoV, sensitivity, wavelength range)

Classification of the Dark Energy Task Force

Albrecht+2006: Report of the Dark Energy Task Force

Performance of a survey quantified in terms of gain in the DE figure of merit (i.e reducing the area of the 95% confidence limit in the $w_0 - w_a$ plane)

2dF, SDSS

- Stage II: observational status in 2010

BOSS / SDSS-III *

- Stage III: experiment started in the 2010s

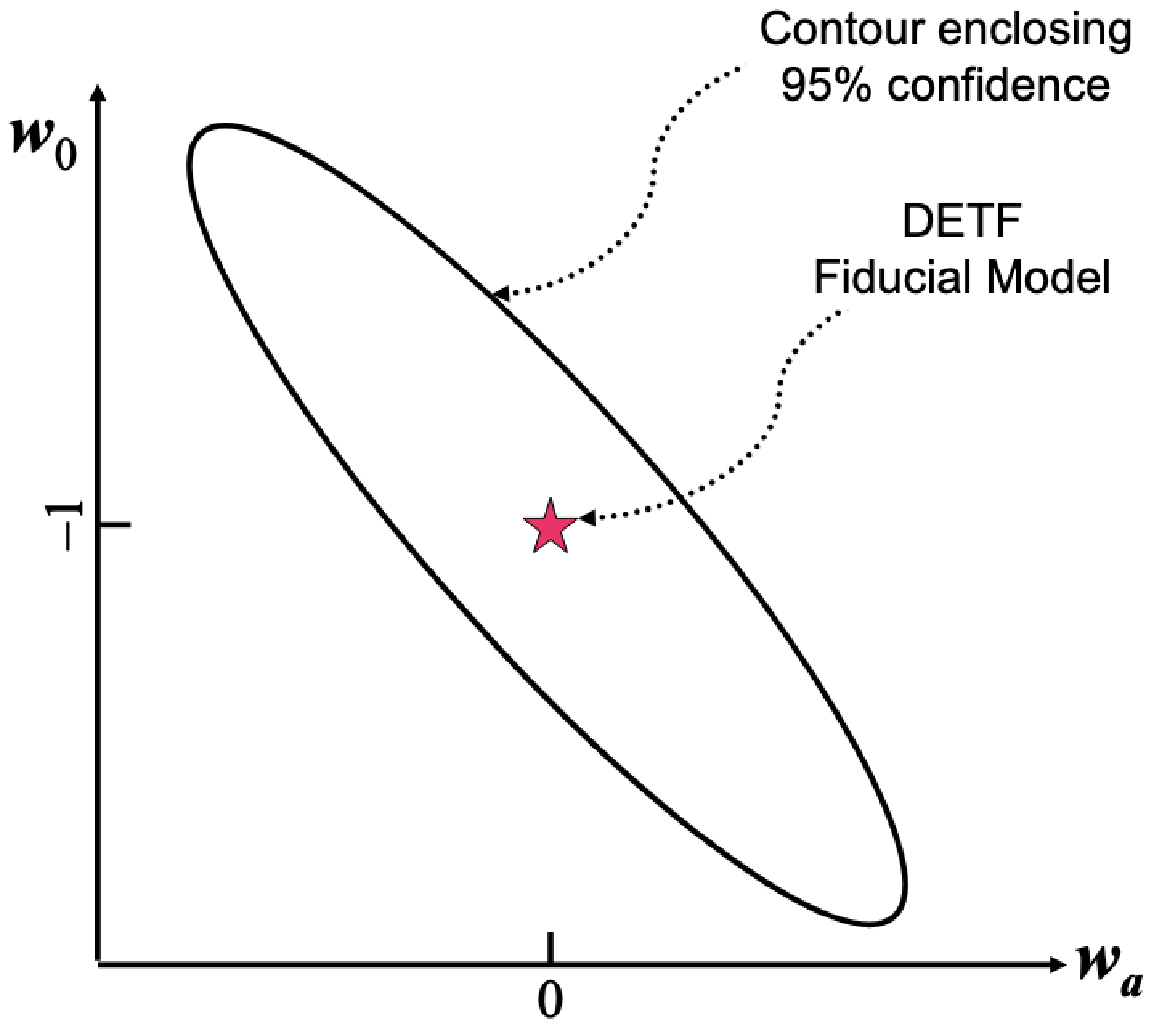
eBOSS / DES / HSC / KIDS-1000 *

- Stage IV: experiments started in the 2020s

DESI/ DESI-II / Euclid / LSST / Roman *

- Stage V?

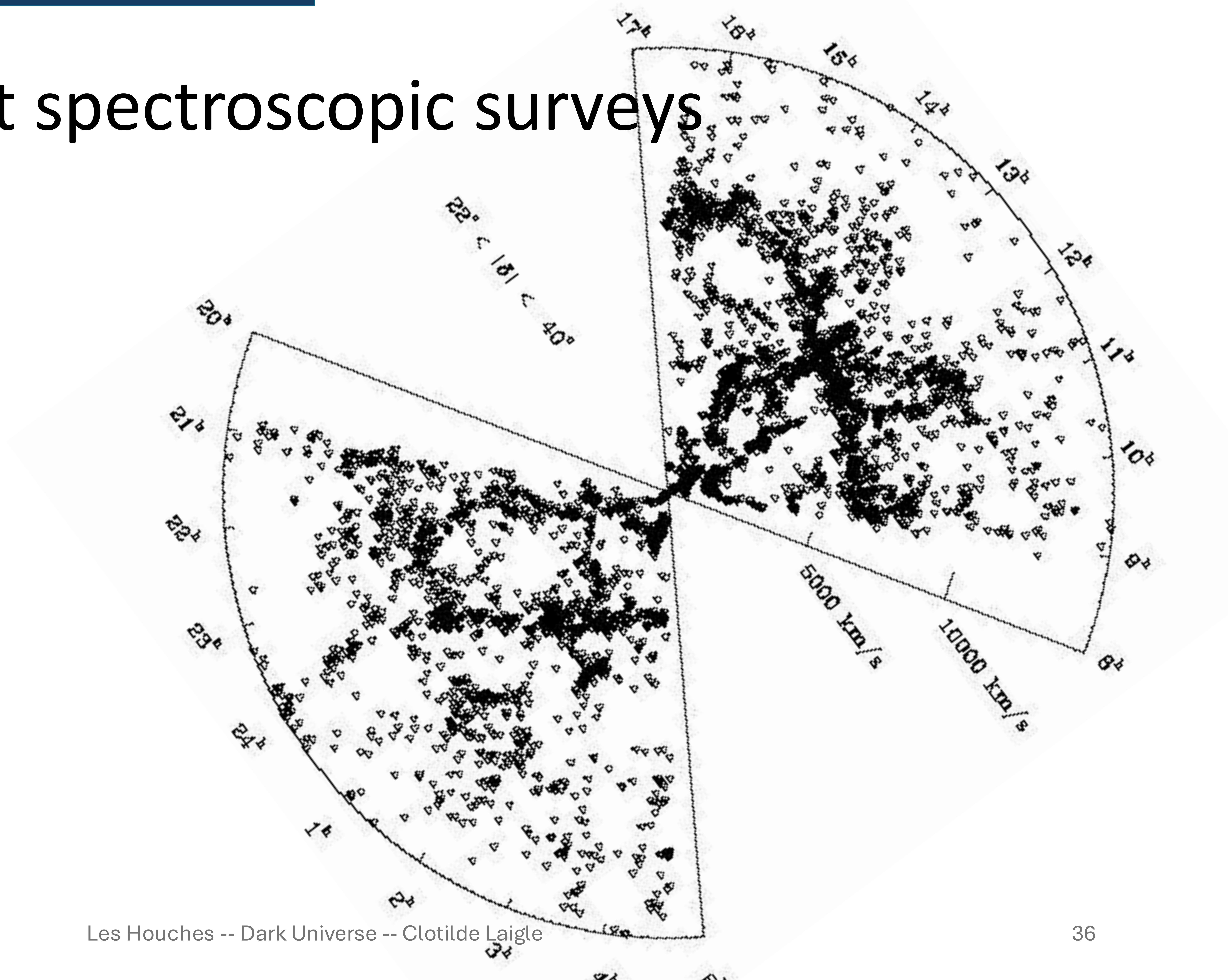
Spec-5: https://spec-s5.org/ Besuner+25, Schlegel+22, WST



*non-exhaustive list

Overview of past spectroscopic surveys

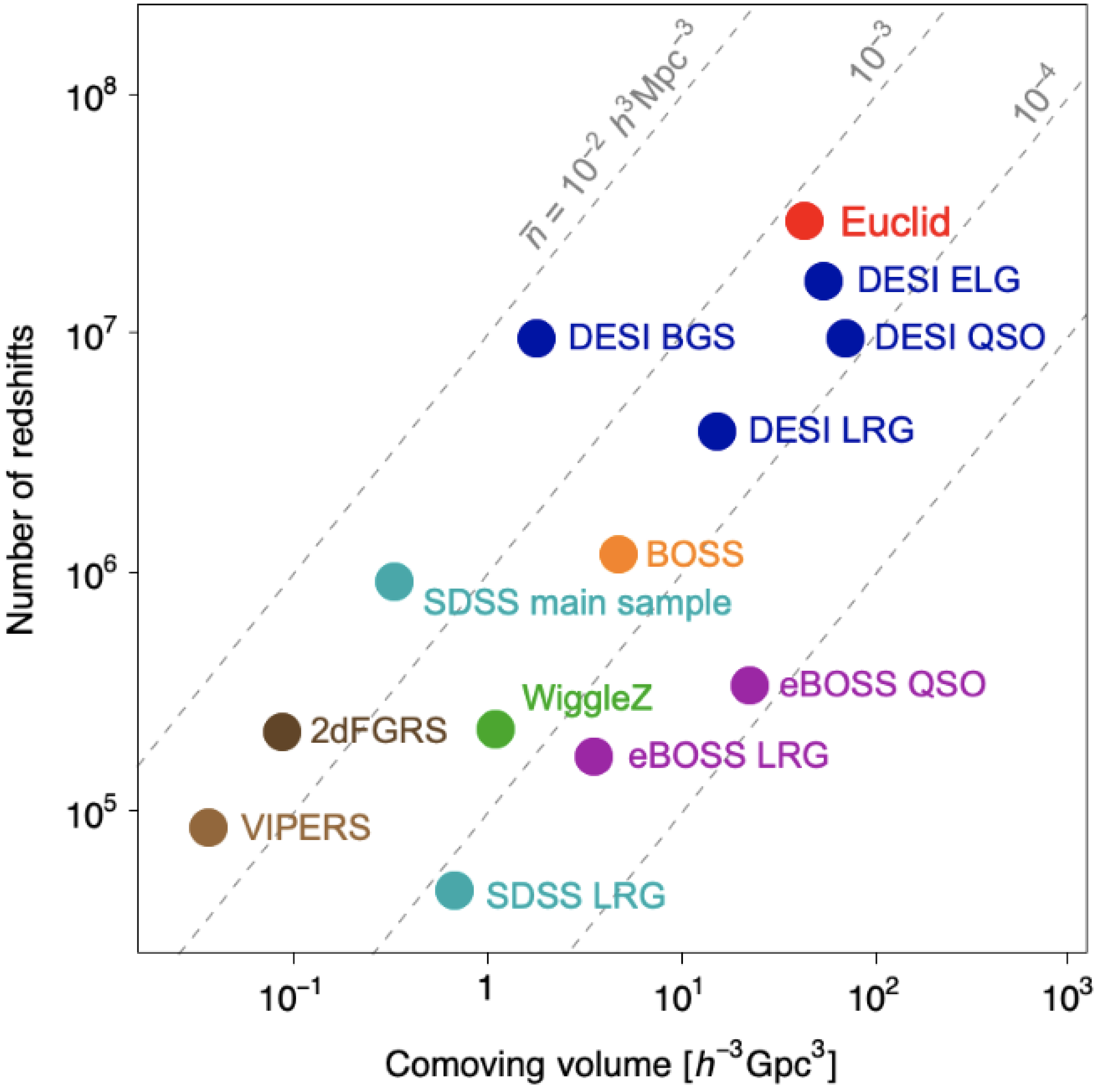
Giovanelli&Haynes+91
Sandage 1975
 Rood 1988



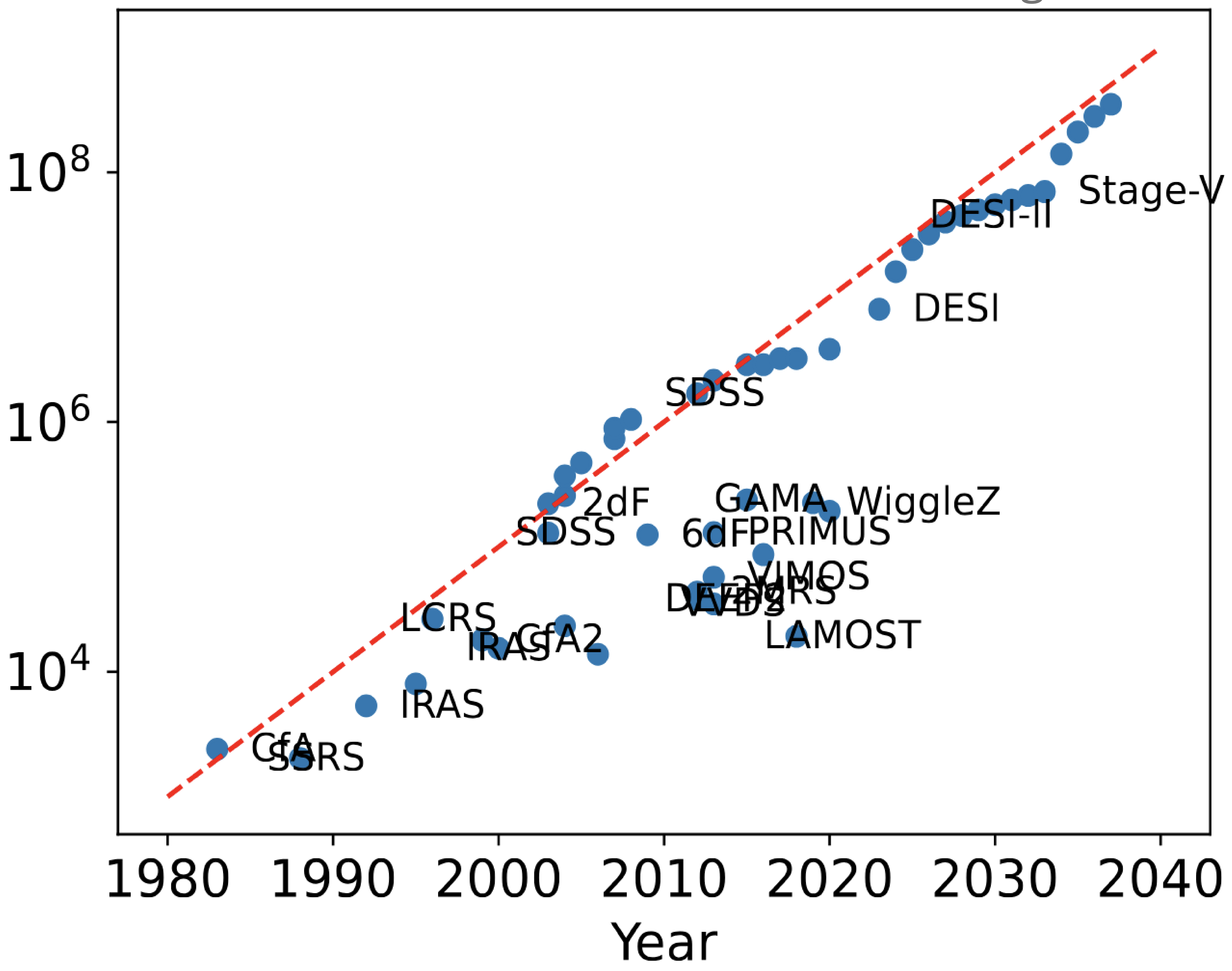
CfA2 and SSRS2 redshift surveys,
Chincarini, G., & Guzzo, L., 1998

Spectroscopic surveys: overview

Euclid collaboration, Mellier+25

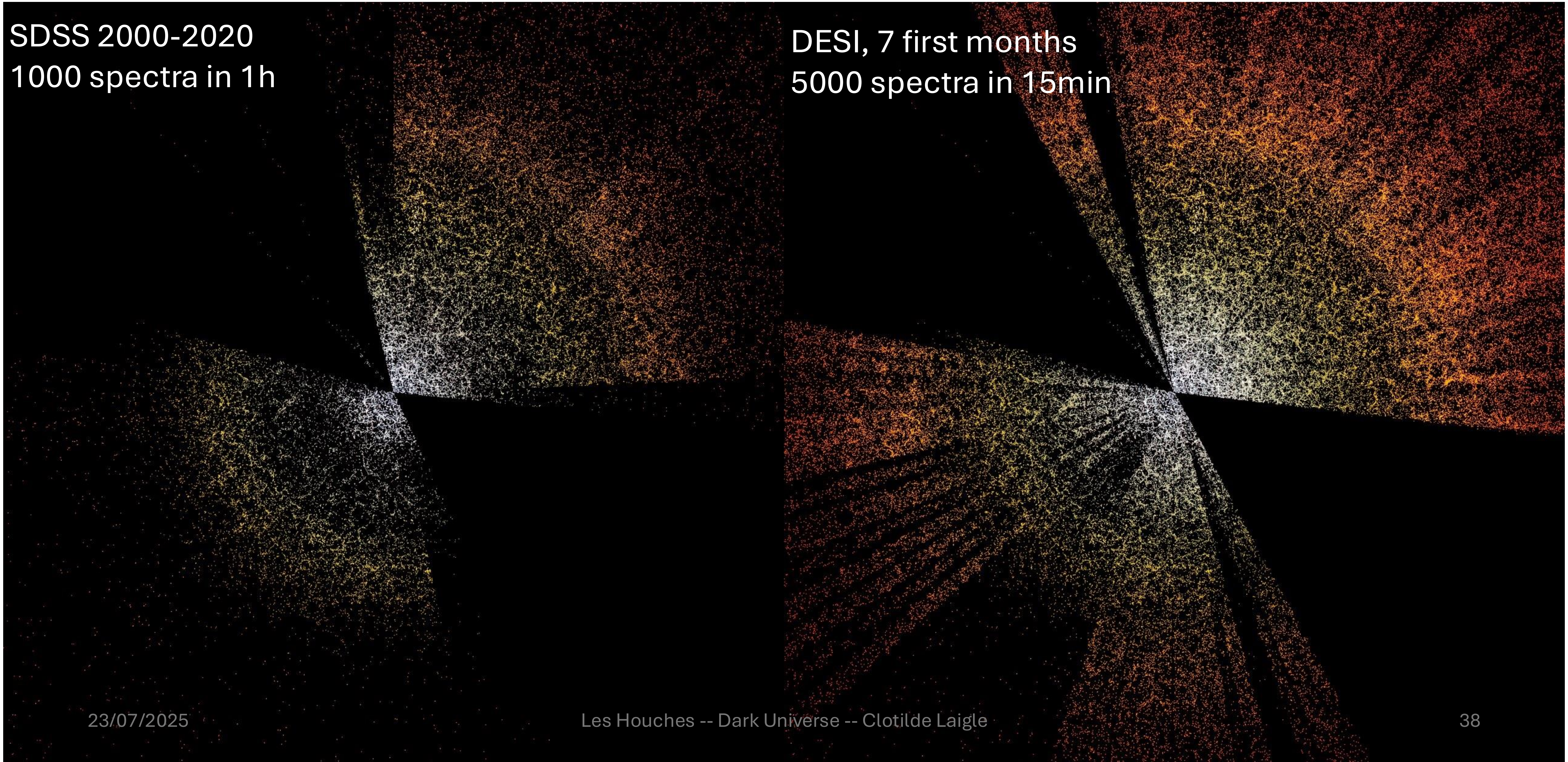


Schlegel+22



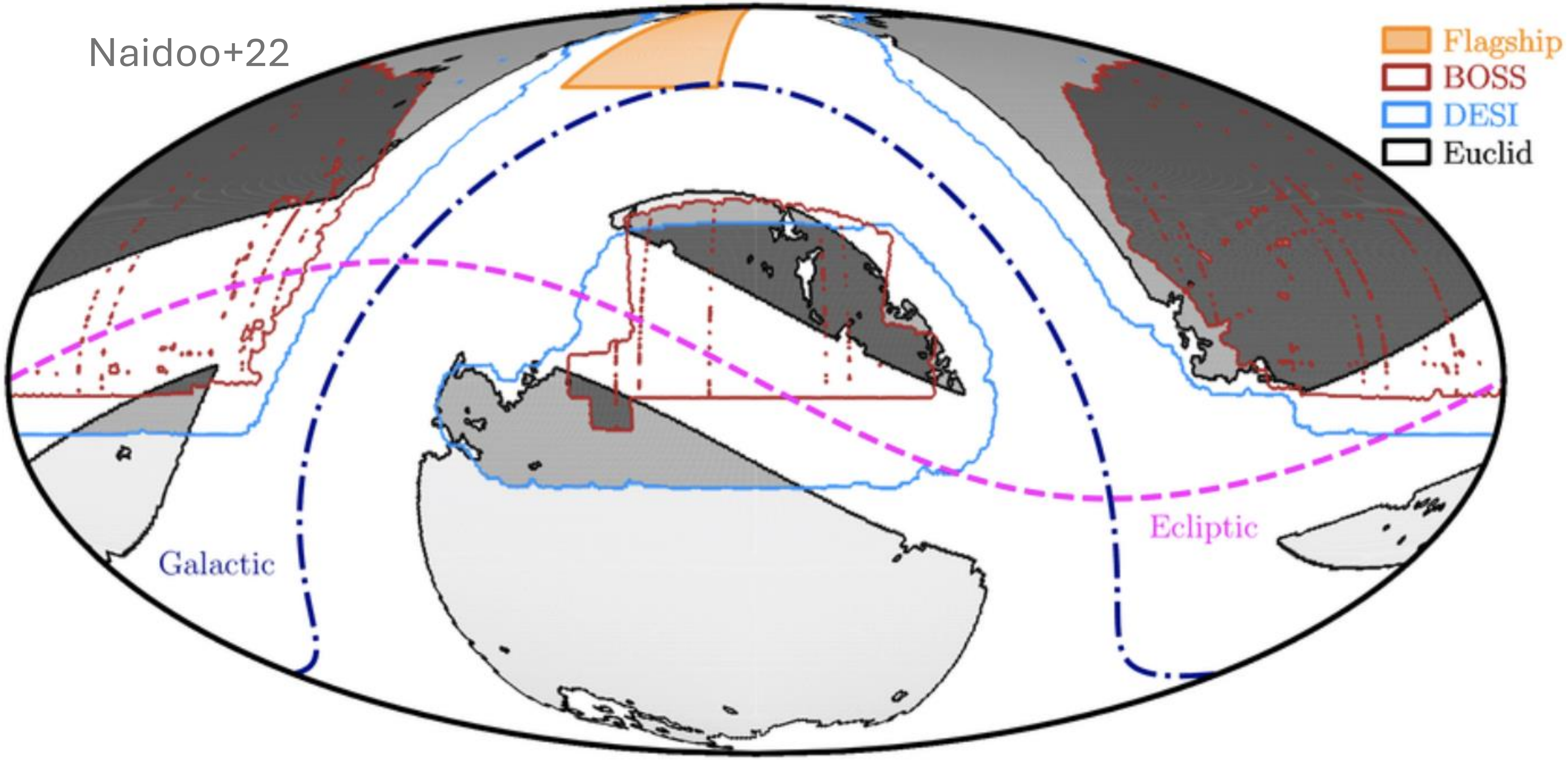
Spectroscopic surveys: overview

Credit: David J. Schlegel (Berkeley Lab using data from DESI)



Spectroscopic surveys: stage IV

Naidoo+22



Spectroscopic surveys: DESI(-II)

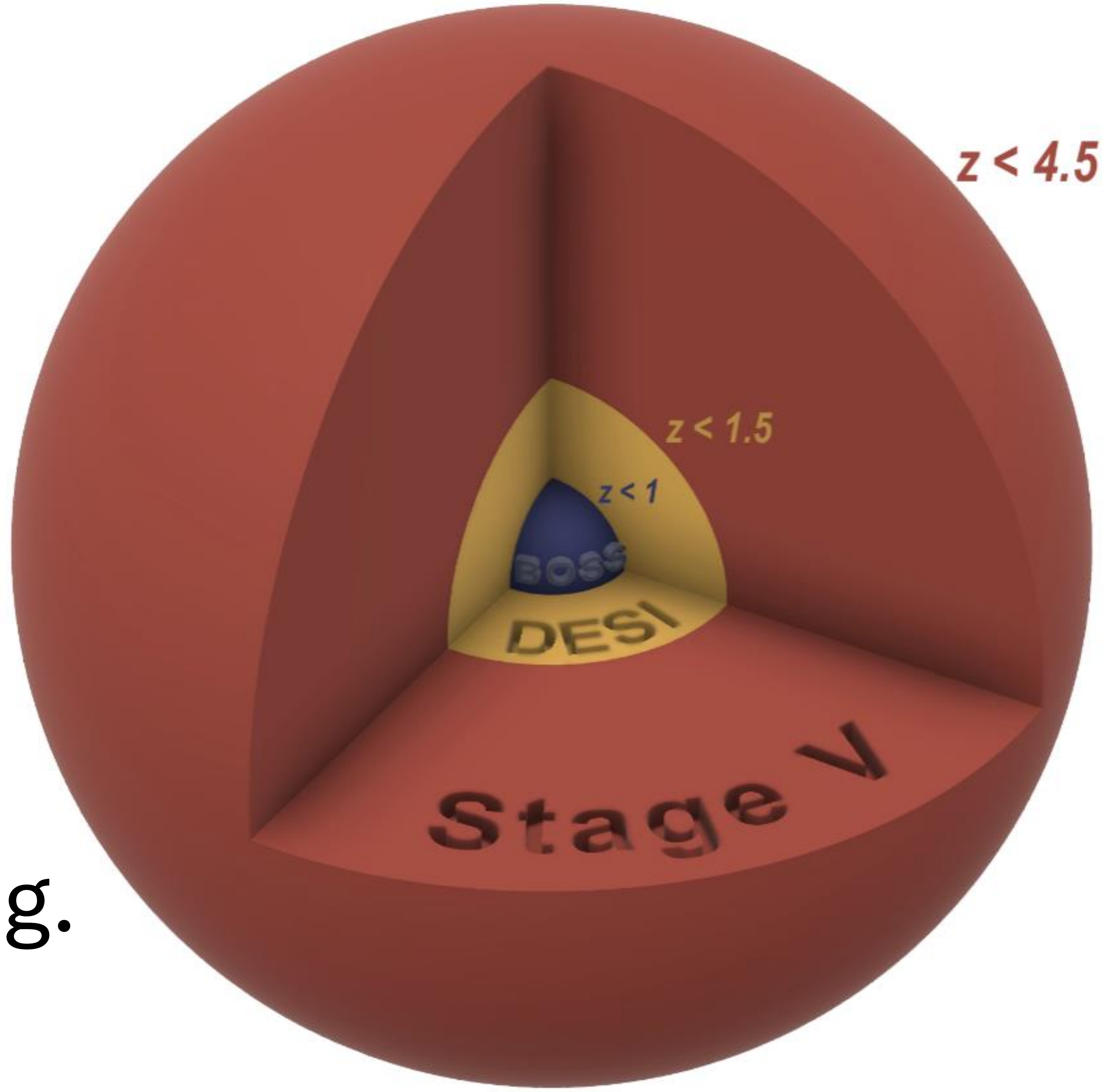
- Kitt Peak observatory (Arizona). 4m telescope
- 5000 fibres, FoV 8 deg^2
- 700 "effective hours" per year = dark, clear time with good (1.1 arcsec) seeing

- **DESI (2021-2026)** 14000 deg^2 (360-980 nm)
  - hundreds of millions of redshifts (~8000 gal/ deg^2)
  - Selection using flux /color cuts to deliver galaxy samples at a optimized density given observation constraints
    - BGS 13.5 million galaxies $0.05 < z < 0.4$
    - LRGS 8 million galaxies $0.4 < z < 1.1$
    - ELG [OII 372] nm 16 millions $0.6 < z < 1.6$
    - QSO+ Lyman-alpha 3 millions $0.8 < z < 3.5$
- **DESI-II (2029-2035)** $> 10000\ deg^2$
  - probe $2 < z < 4.5$ Universe with LAEs (Lyman Alpha Emitters) and LBGs (Lyman Break Galaxies)
  - higher-density z < 1 galaxy sample

Spectroscopic surveys: stage-V DE experiments

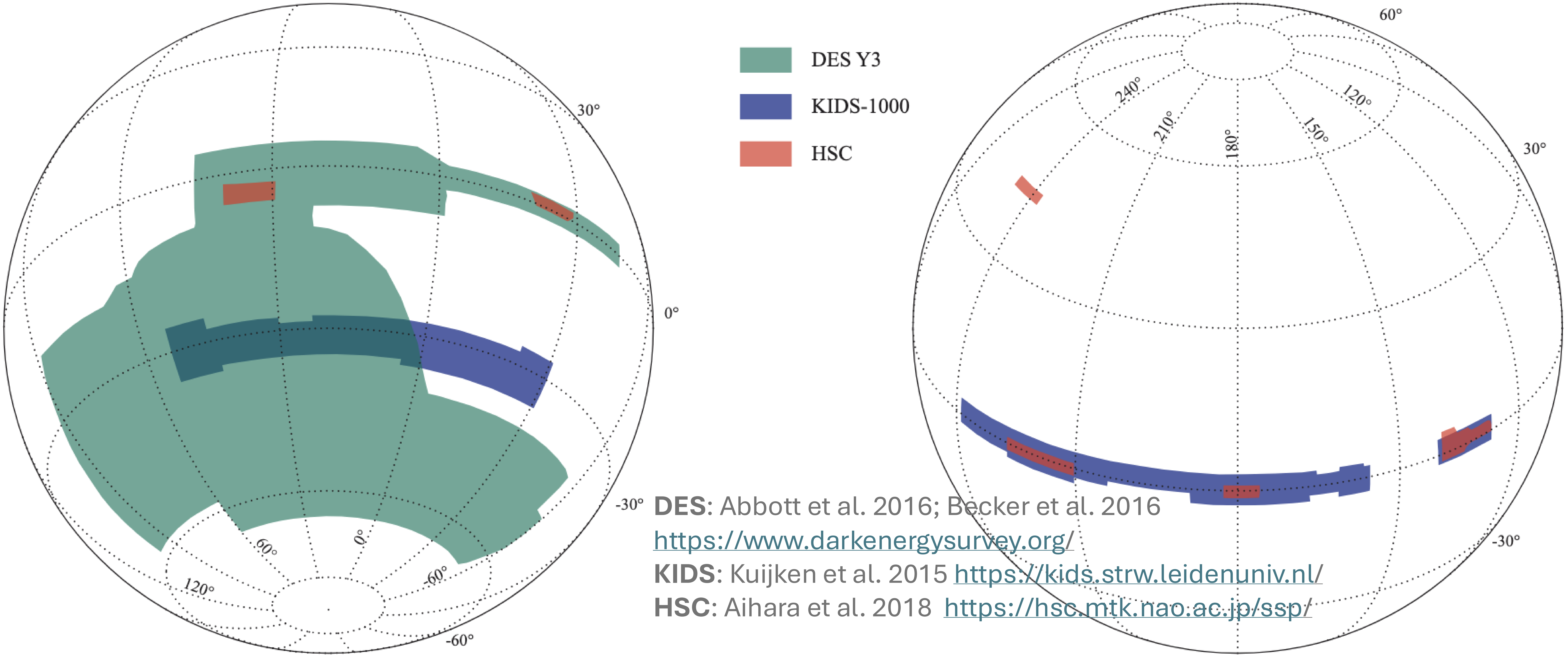
- Aim:
  - Extend redshift coverage
  - Extend galaxy density
- Technical improvements:
  - Extend primary mirror size
  - More fibers positioners => 15 faster than DESI
  - Extend wavelength coverage
- Need: imaging survey for target selection (e.g. LSST) esp. dropouts LBG at z>2

Credit: C. Yeche



Photometric surveys: overview of stage-III DE experiments

Secco+22



DES: Abbott et al. 2016; Becker et al. 2016
https://www.darkenergysurvey.org/
KIDS: Kuijken et al. 2015 https://kids.strw.leidenuniv.nl/
HSC: Aihara et al. 2018 https://hsc.mtk.nao.ac.jp/ssp/

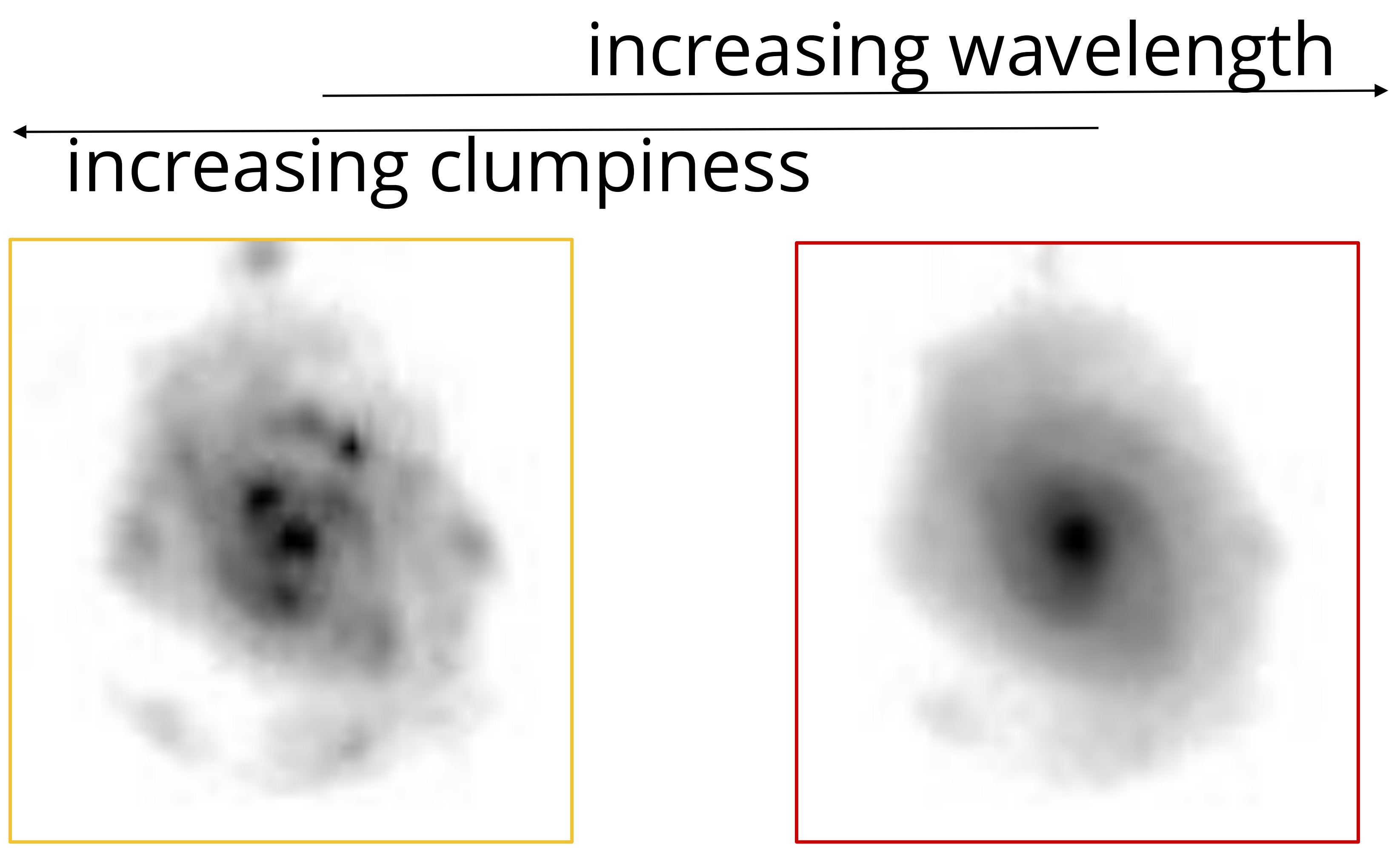
Photometric surveys: overview

	Survey	res arcsec	Area deg^2	Bands nm	depth	density gal/arcmin^2
Stage-II	SDSS-III 2000 –		10000	*ugriz*	$r \sim 23.5$	2
Stage-III	HSC-SSP [3] 2014 –	0.58	1400	*grizy*	$r \sim 26.1$ (5σ)	20
	DES [4] 2013 – 2019	0.96	5000	*grizY*	$r \sim 24.3$ (10σ)	6
	KiDS	0.7	1350	$ugri(+ZYJHK_s)$	$r \sim 25$ (5σ)	6
Stage-IV	Euclid 2023-2030	0.16	14000	VIS+YJH	$I_E \sim 24.5$ (10σ)	30
	LSST 2025 – 2035	0.7	18000	*ugrizY*	$r \sim 27.5$ (5σ)	30
	Roman 2026 – 2032	0.2	2000	*YJH*	$Y \sim 26.5$	50

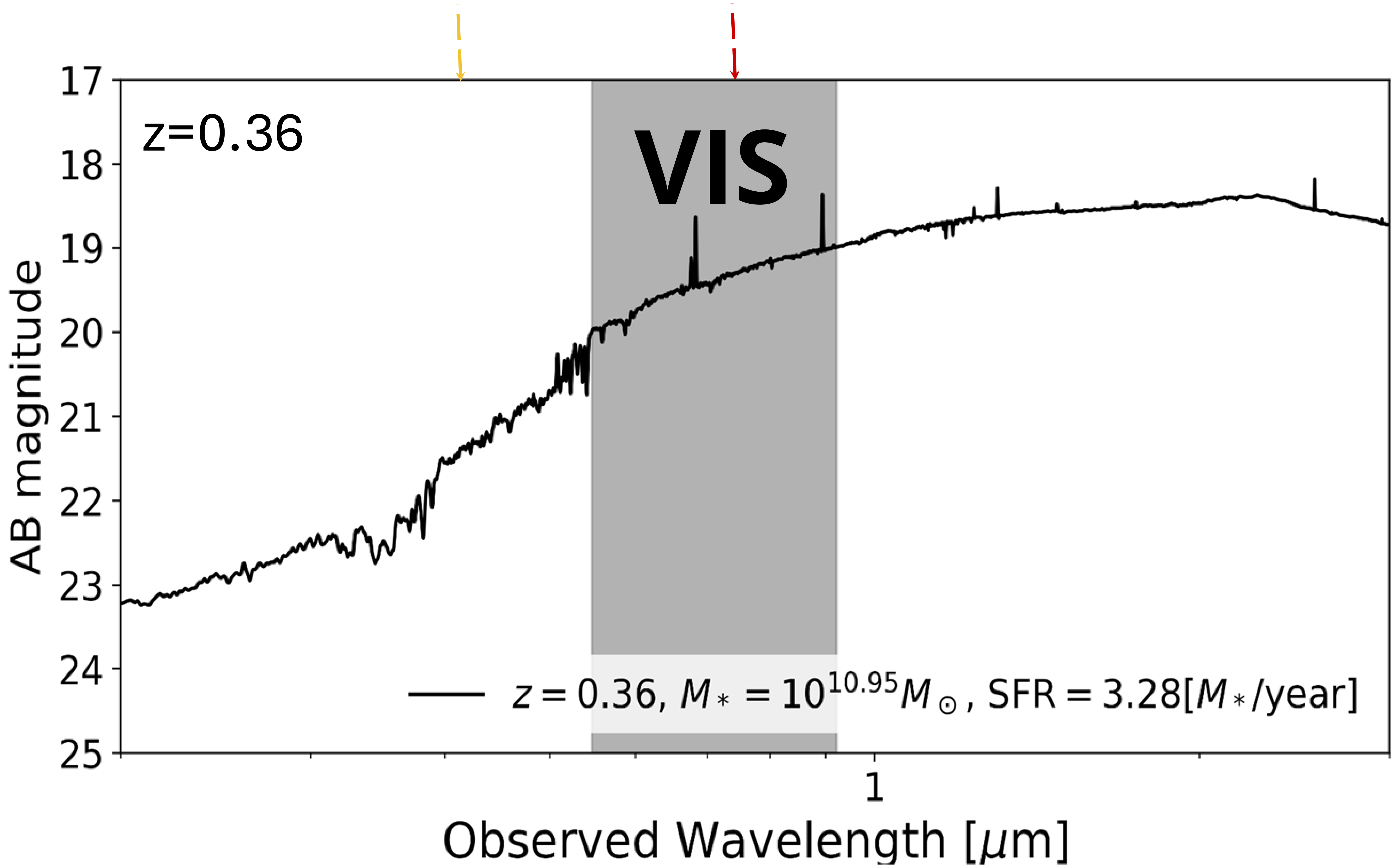
Galaxy WL: choice of filter passbands

A broad red band is preferred to **limit clumpiness** and maximise the number of sources

But angular resolution decreases witł



149.94090 +1.82834 eq
Subaru B and i+ bands



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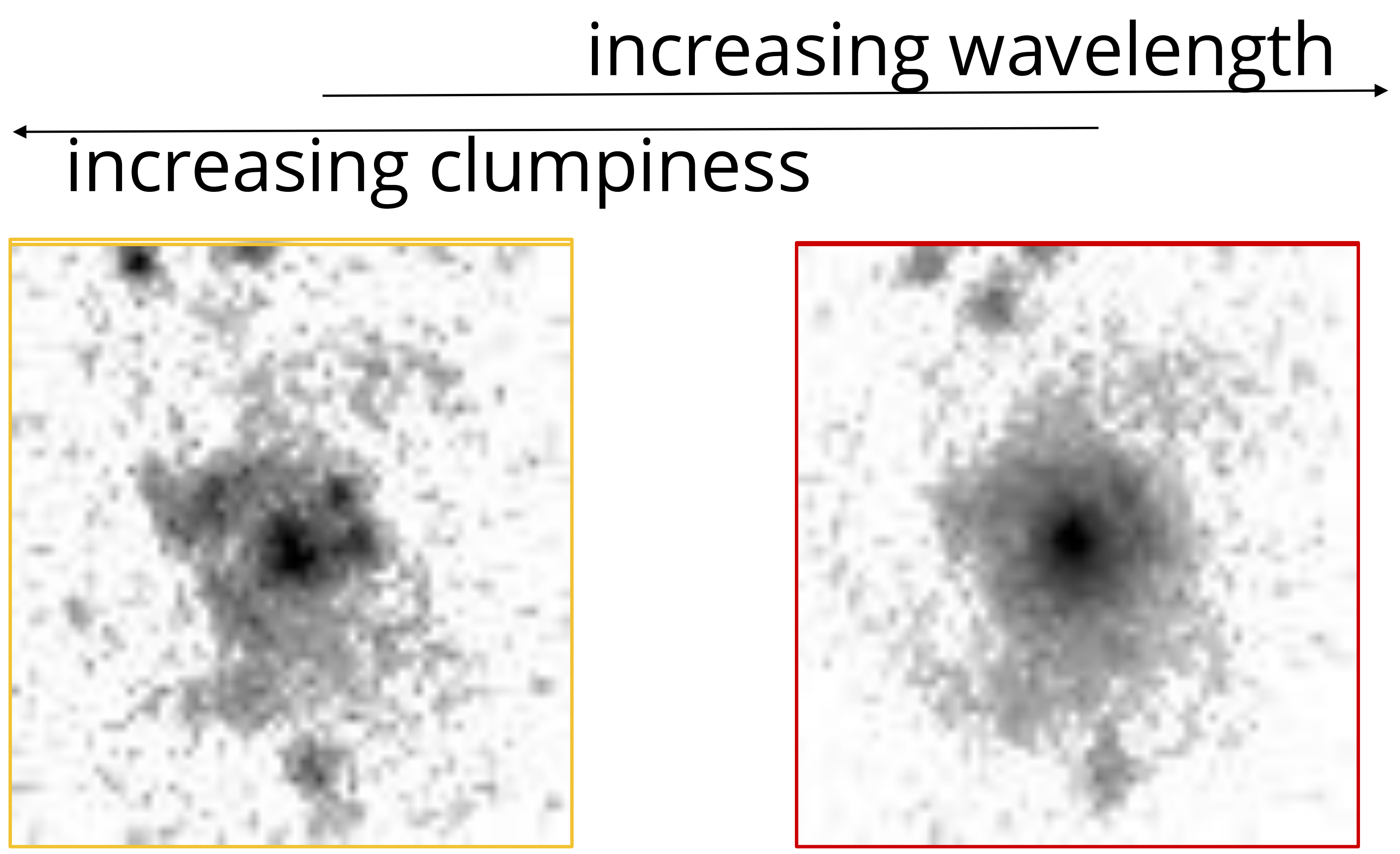
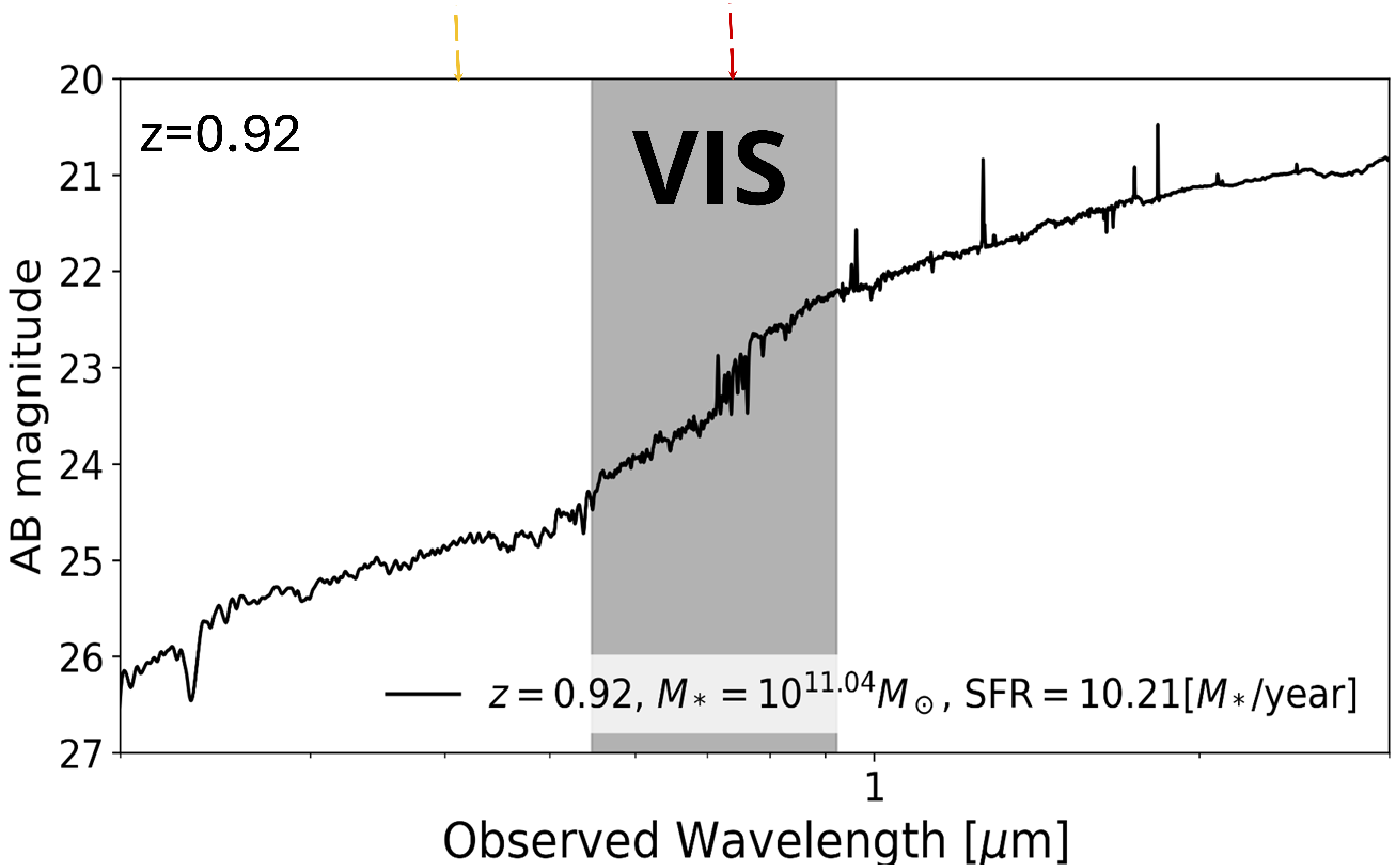


150.55381 +2.53197 eq
Subaru B and i+ bands



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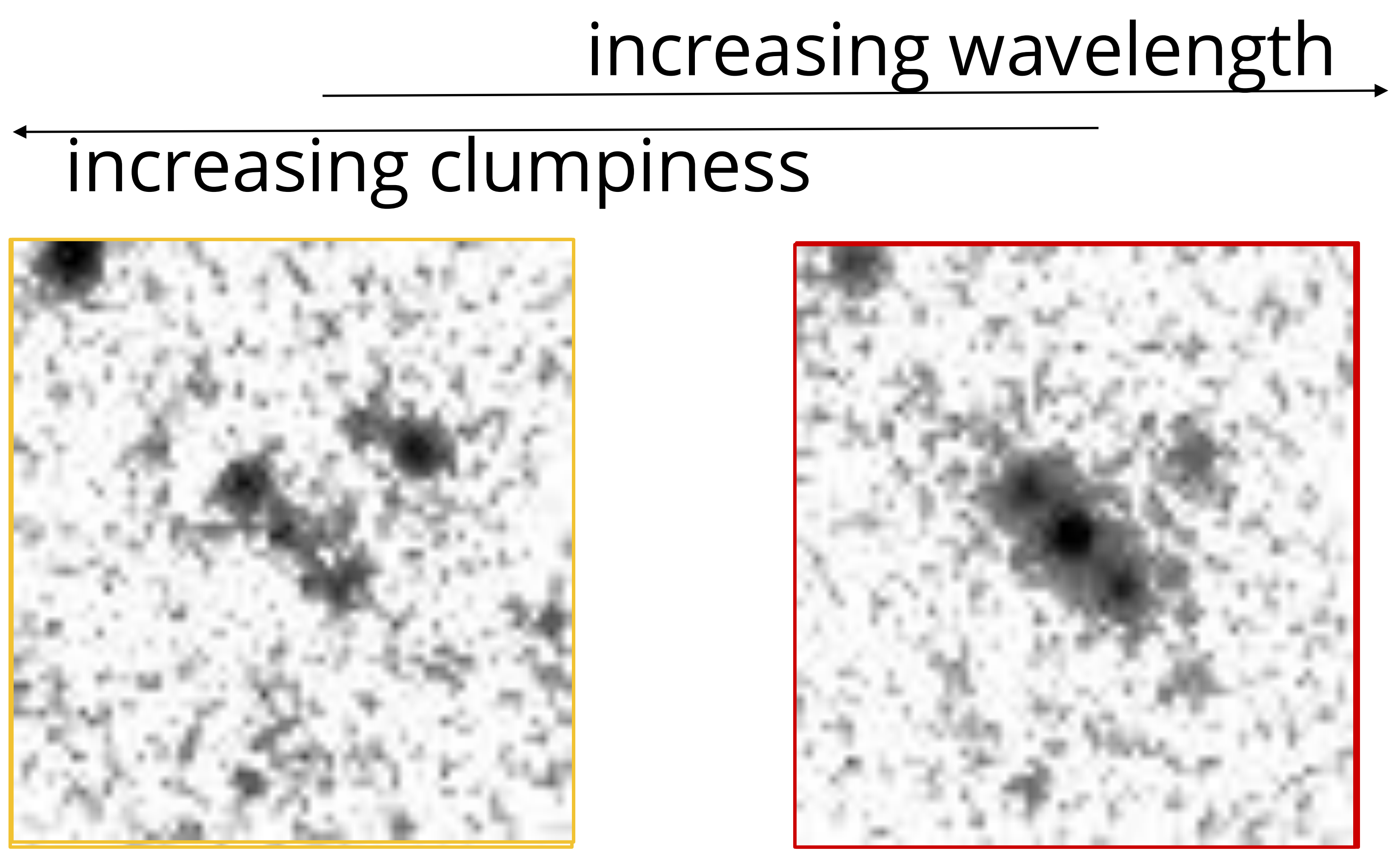
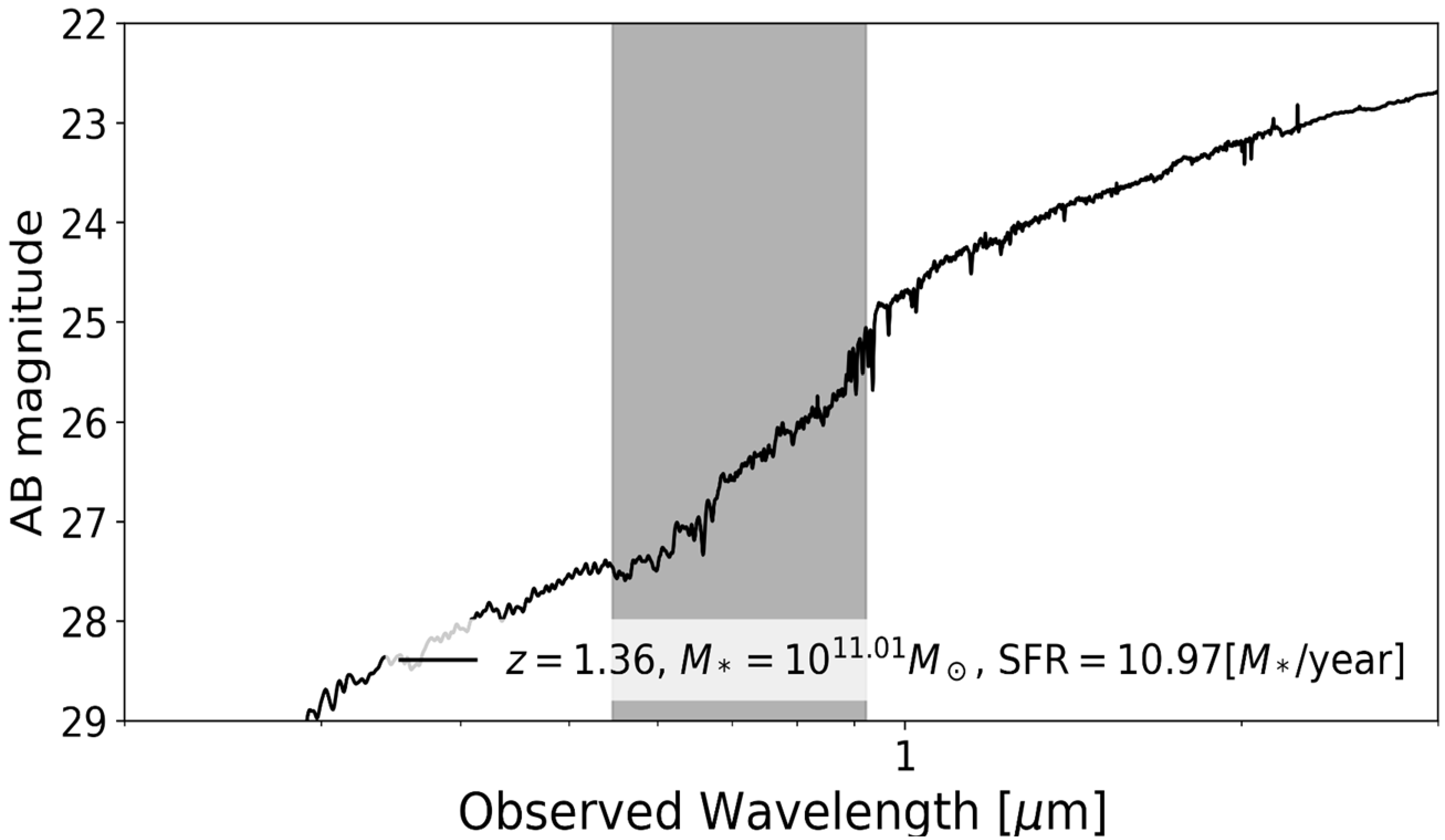


149.66106 +1.69547 eq
Subaru B and i+ bands

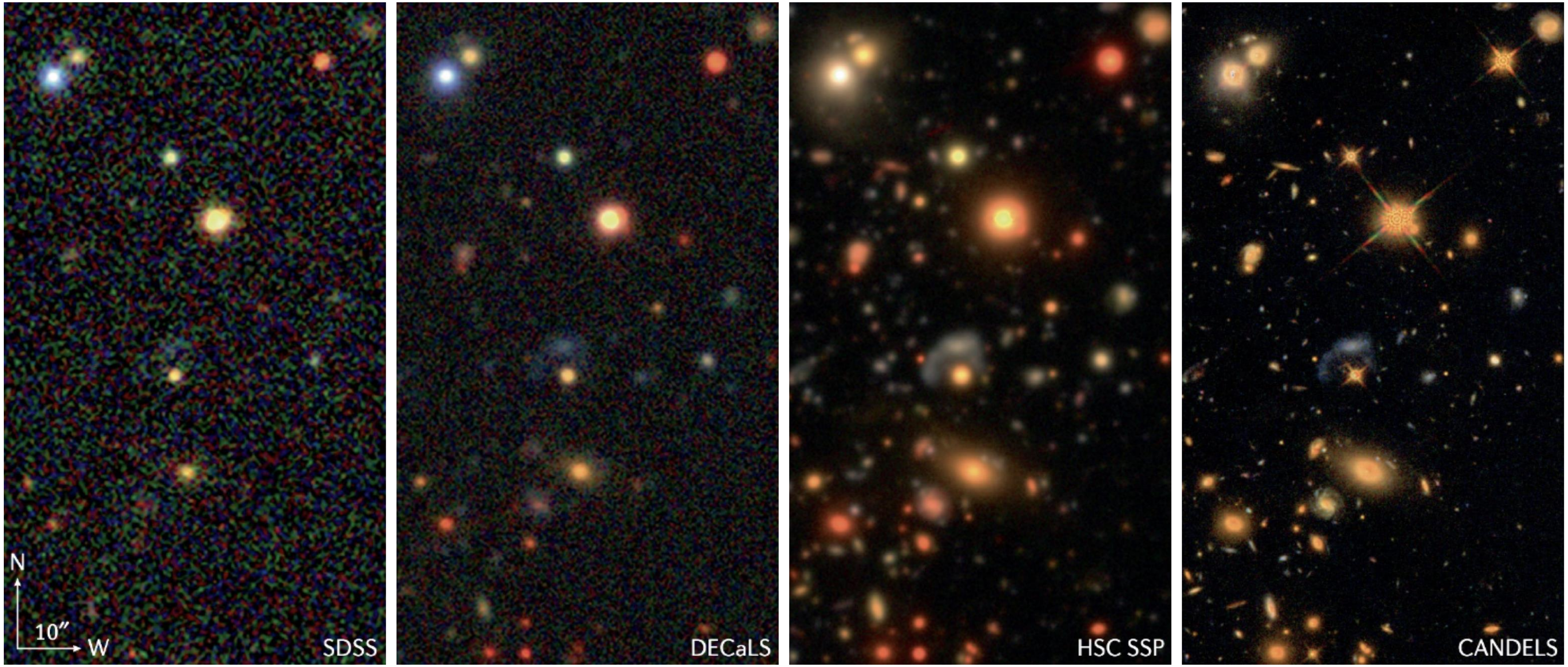


A major step forward with Euclid

Melchior, P+2021

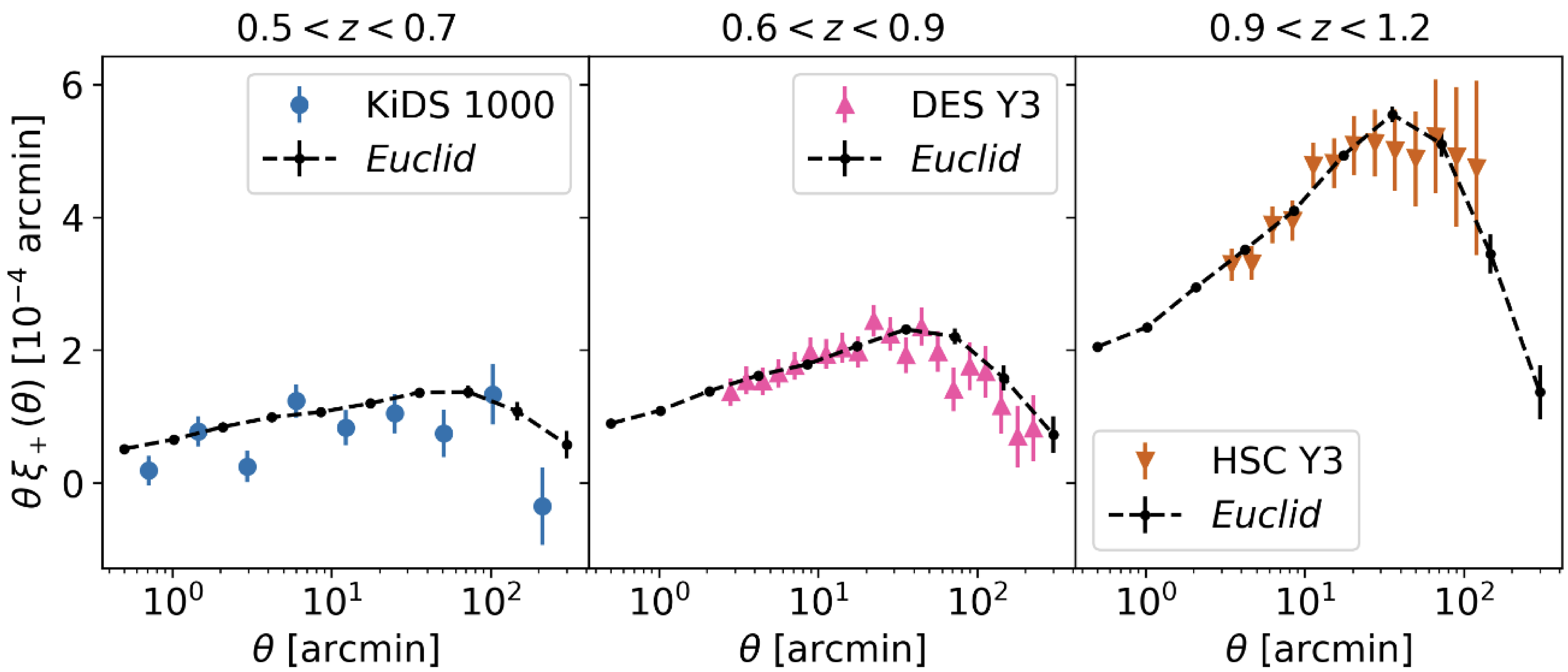
HSC

Similar to Euclid



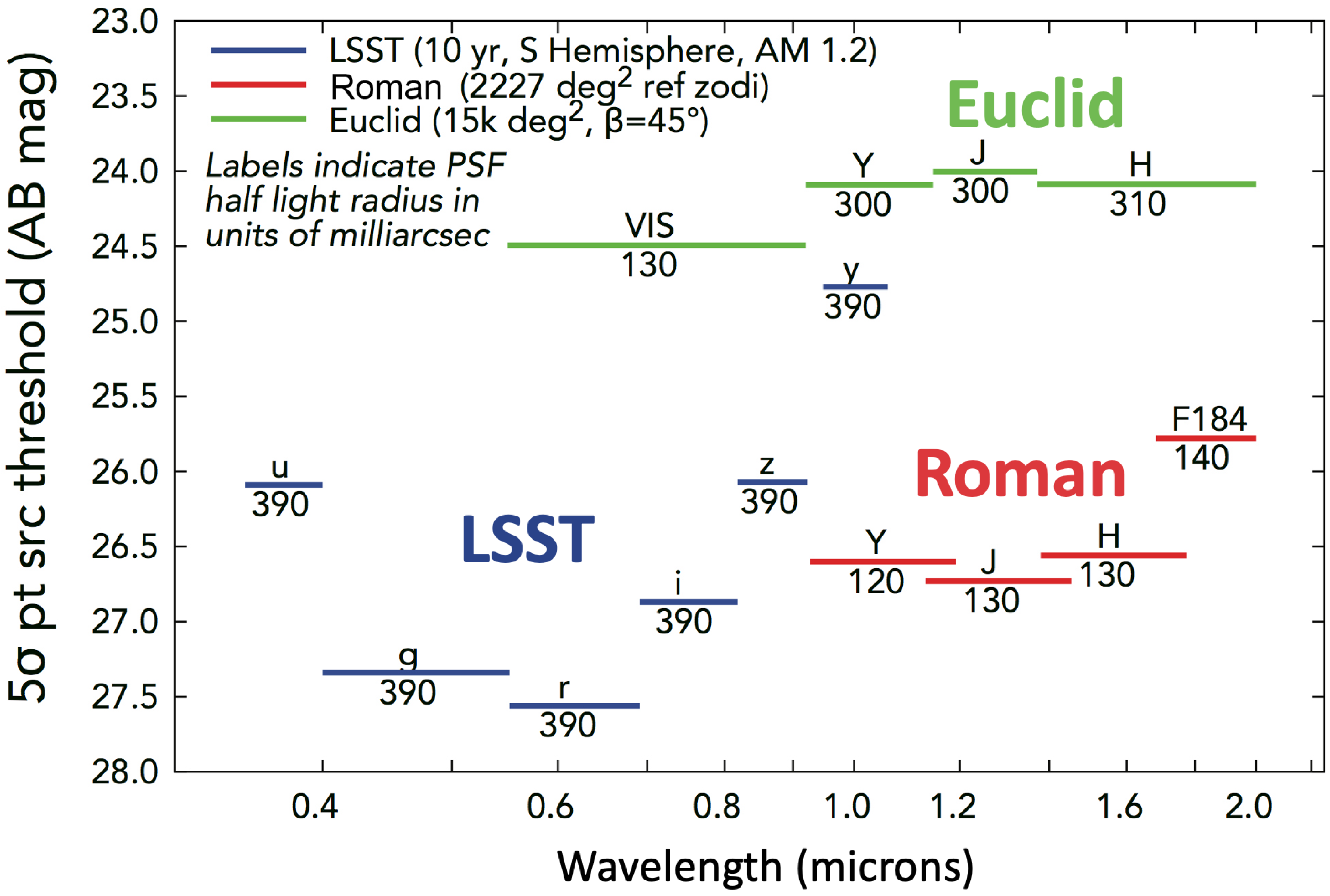
A major step forward with Euclid

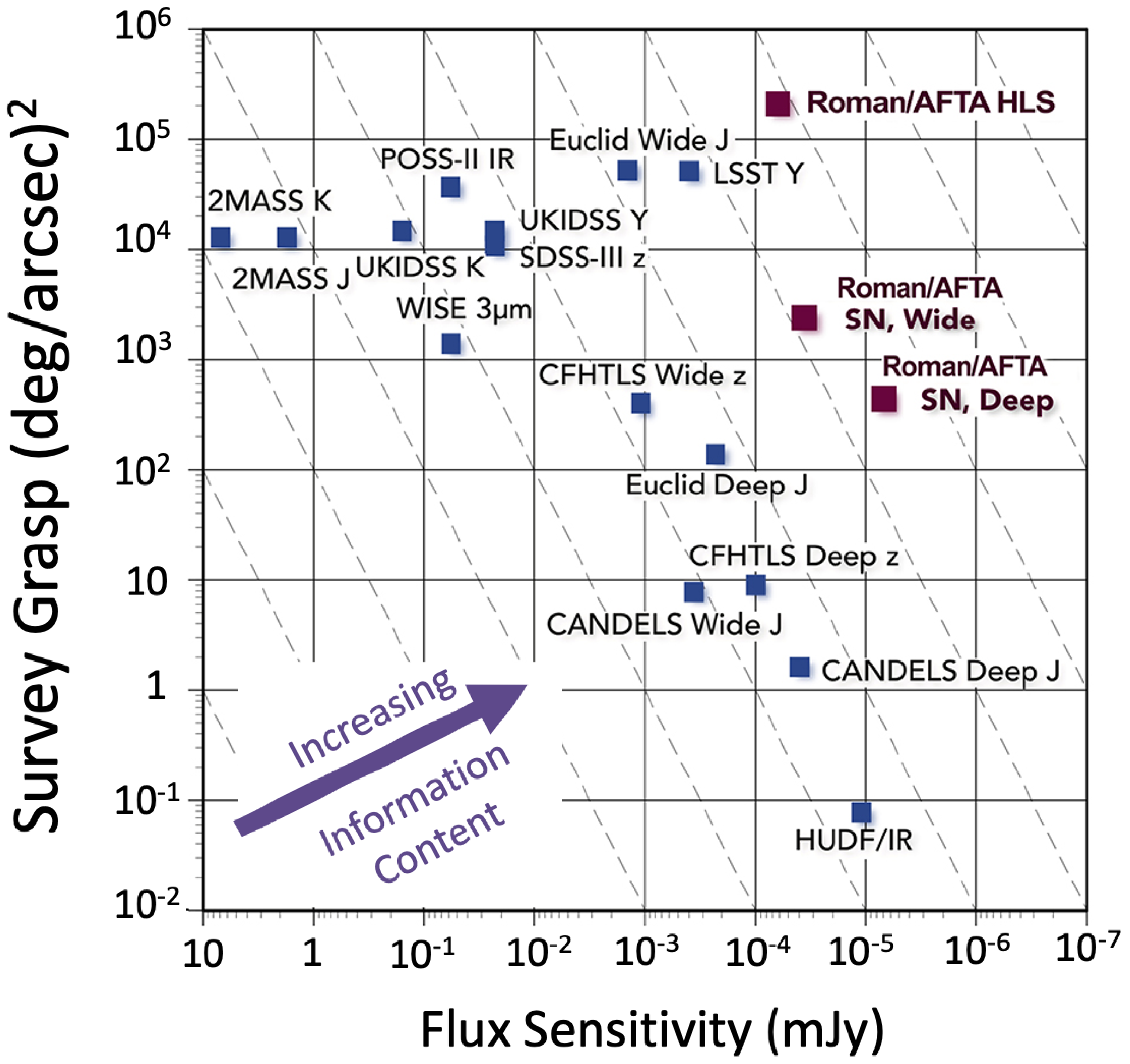
Euclid collaboration Mellier+25



V. Rubin: Ivezic et al. 2019
Euclid: Laureijs et al. 2011
Roman: Akeson et al. 2019

Euclid, V. Rubin, Roman observatories in comparison



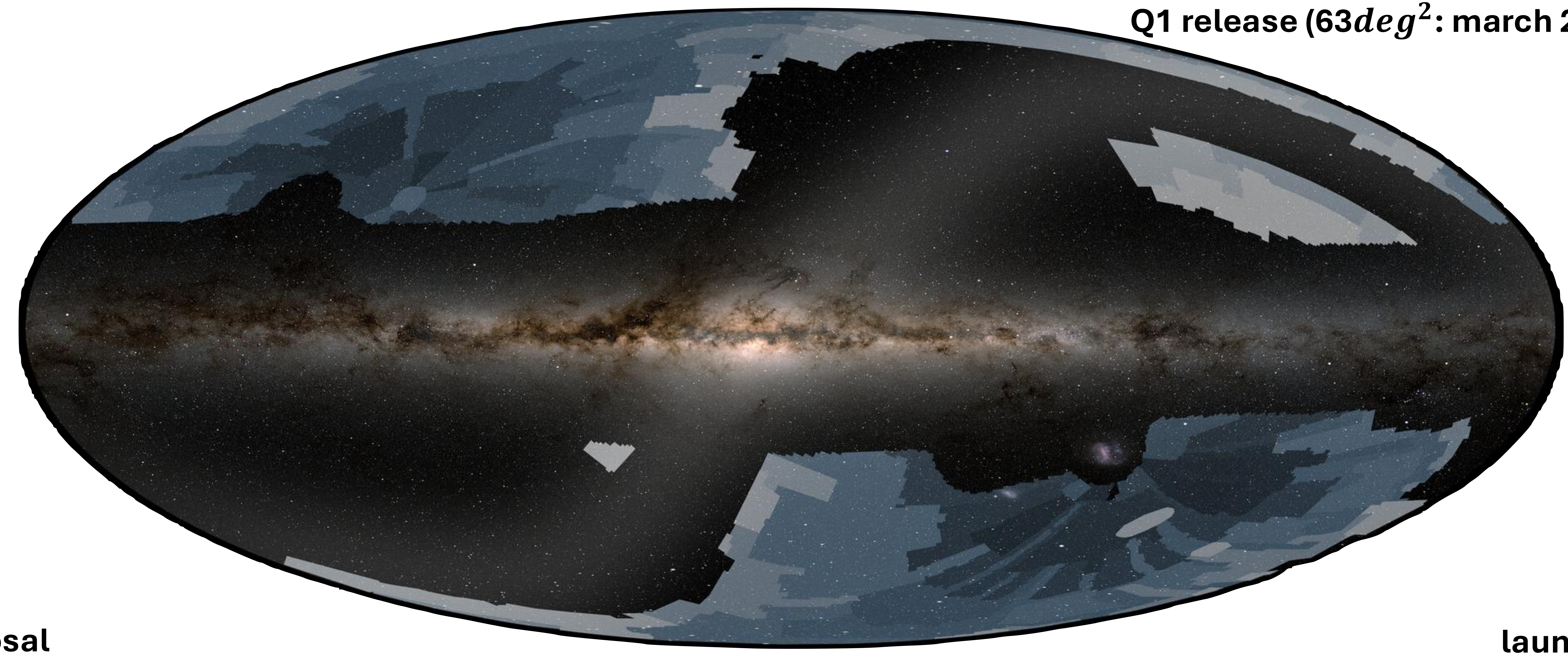


Credit: NASA

Overview of Euclid

Euclid collaboration: Mellier et al. 2024

Scan 14000 deg^2 in 6 years
Need on-ground complementary data for redshift computation
DR1 release (1900 deg^2: oct. 2026)
Q1 release (63deg^2: march 2025)



proposal **launch**

2007 → **2012** → **2023**

https://www.cosmos.esa.int/web/euclid/euclid-q1-data-release

Euclid Quick data release 1

Euclid collaboration: Mellier et al. 2024

Scan 14000 deg^2 in 6 years
Need on-ground complementary data for redshift computation
DR1 release (1900 deg^2: oct. 2026)
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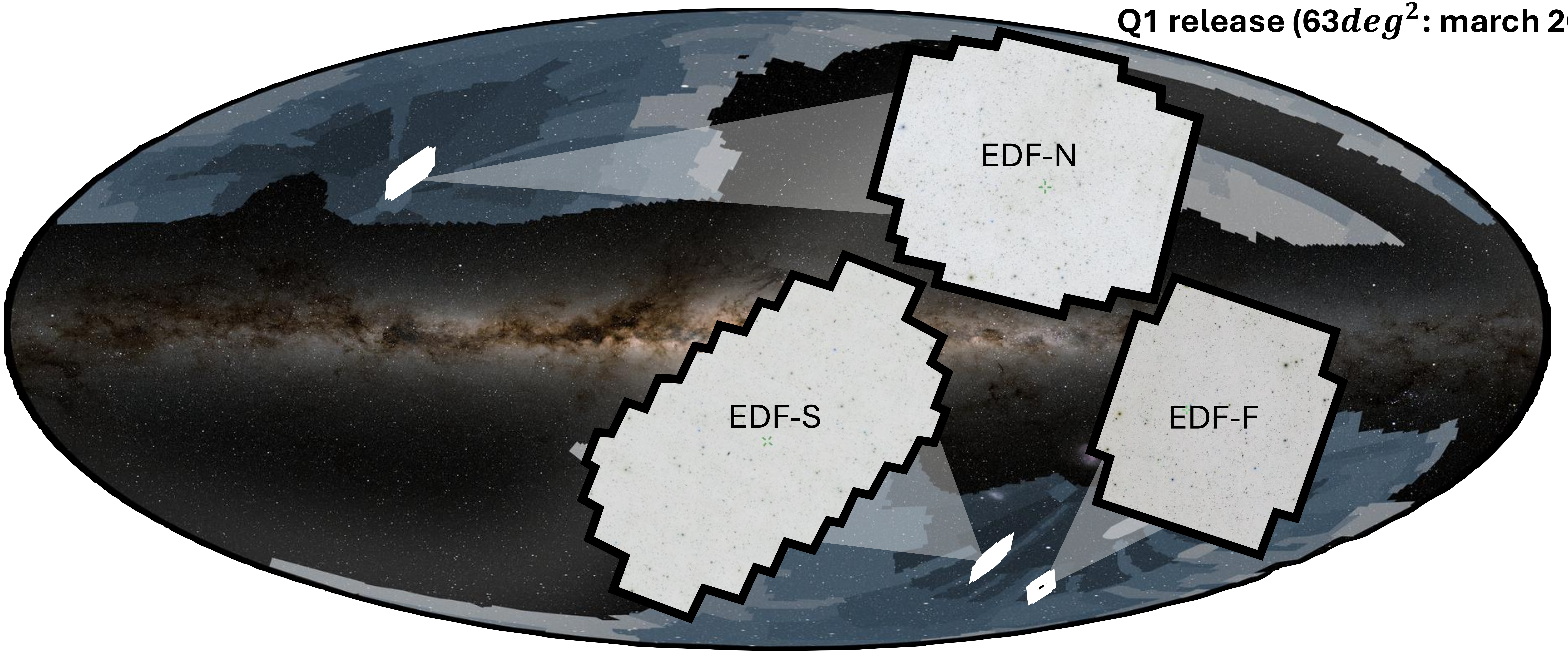


2007 → **2012** → **2023**

Overview of Euclid: 2 instruments

NIR spectro-photometer

The NISP will measure redshifts of 25 millions of galaxies, up to z=1.8 over 14000 deg^2 with a grism

Technical characteristics:
- •60 millions of pixel
- •field of view 57 deg^2
- •16 detectors, 0.3" / pixel
- •3 photometric bands
- •2 spectroscopic bands
- •Spectral resolution: R~480

Depths:
24.5 AB mag (5σ point source) and 2e-16 erg/s/cm2 (line flux)

clustering

VISible immager

VIS will measure the precise shapes of > 2 billions of galaxies, and over 14000 deg^2 using photometry (40 000 exposures).

Technical characteristics
- •600 million pixels
- •0.1"/pixel
- •530–920 nm wavelength range defined by coated
- •field of view: 0.55 deg
- •exposure times 10min:

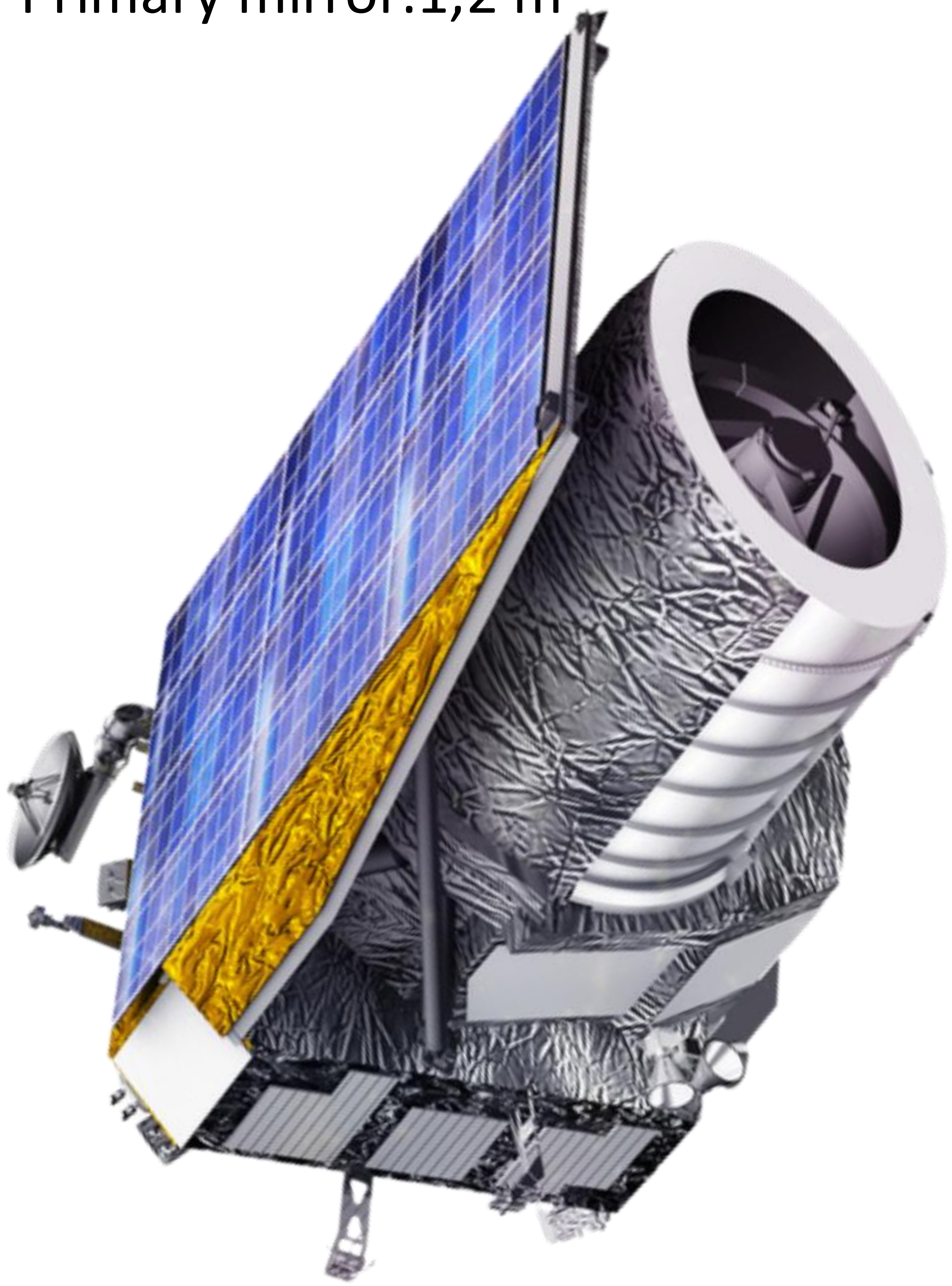
400000 detected galaxies,
with the 50000 most brightest will be used for shape measurements

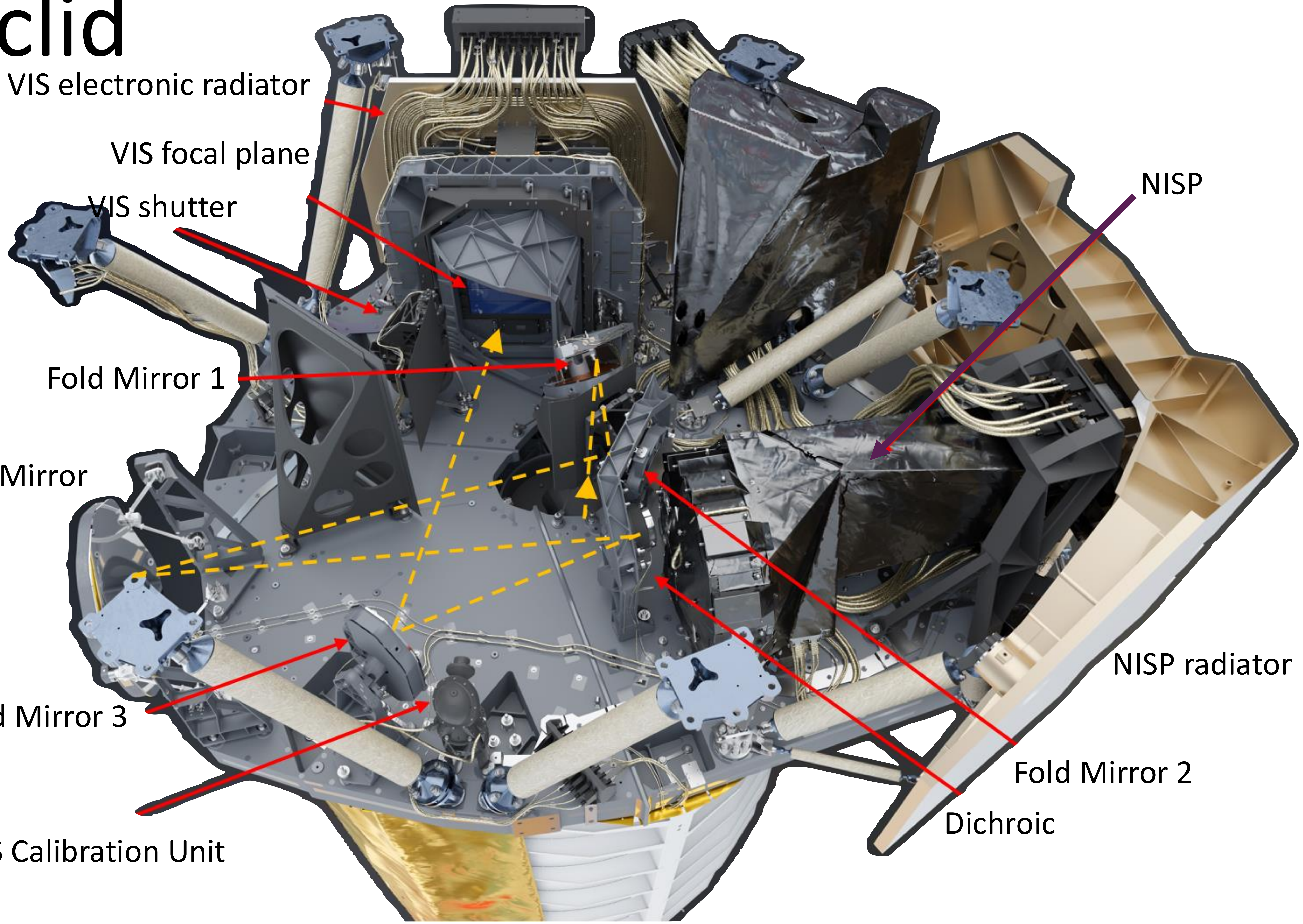
Weak lensing

26.2 AB mag (5σ point source)

Overview of Euclid

Primary mirror:1,2 m





Crédit: Airbus / ESA

3. From distant galaxies to the detector

The example of VIS on Euclid

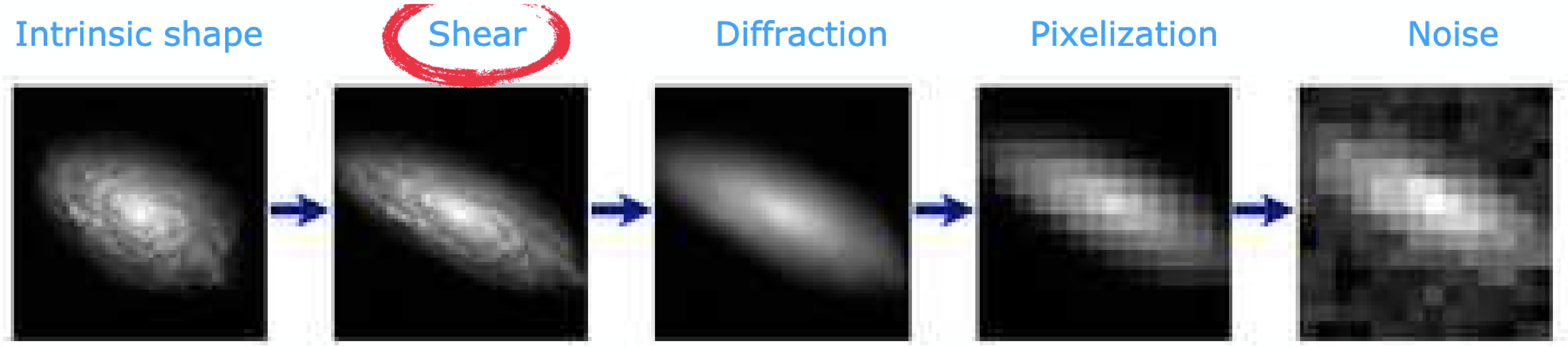
Weak lensing: what do we need

- High accuracy on galaxy shapes
  - ... Requires a clean galaxy catalogue (no artefacts)

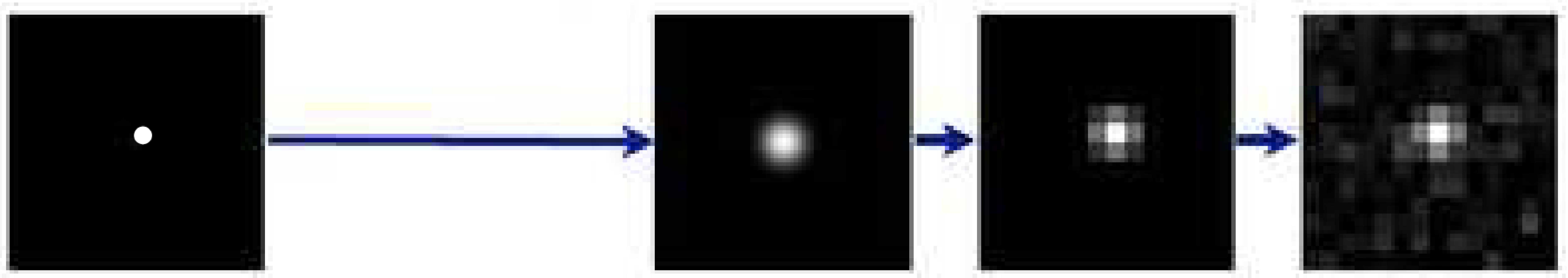
- Reasonable measurement of galaxy fluxes
- Redshift distribution in tomographic slices

What is a galaxy?

What are galaxies in the images?

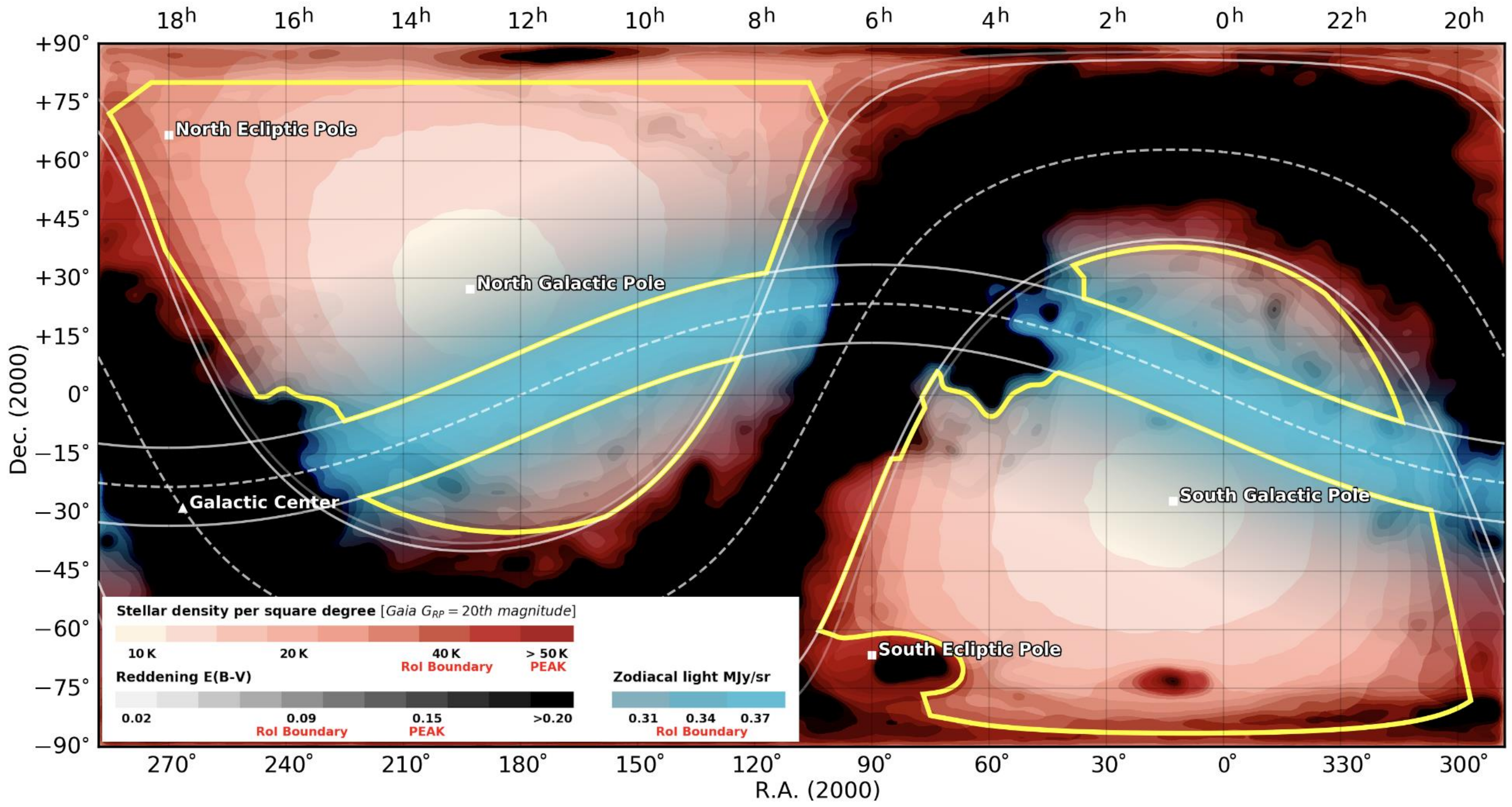


Stars – Point Spread Function



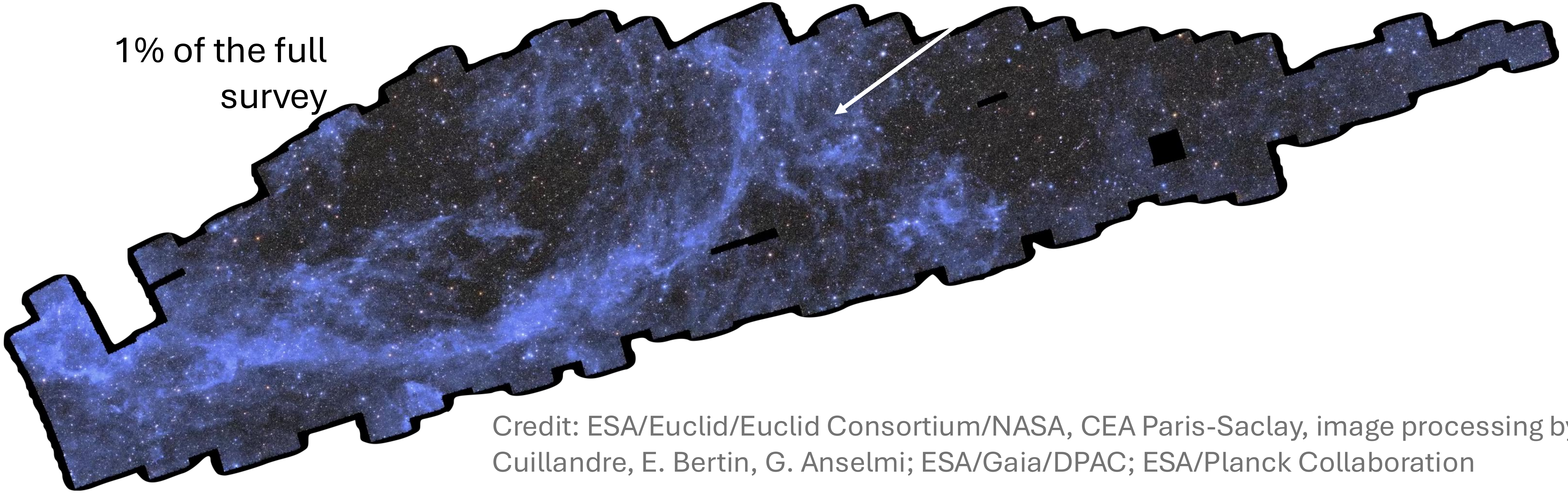
Credit: S. Bridle

What is an object? Sky background extraction



What is an object? Sky background extraction

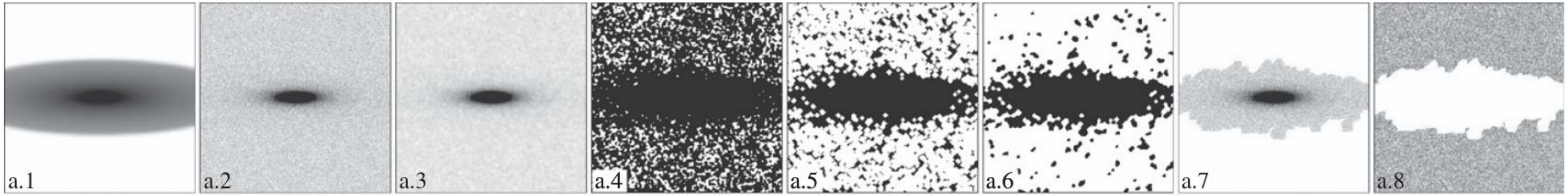
- Background contains mostly zodiacal light and straylight from stars and solar system bodies + cirrus clouds



Credit: ESA/Euclid/Euclid Consortium/NASA, CEA Paris-Saclay, image processing by J.-C. Cuillandre, E. Bertin, G. Anselmi; ESA/Gaia/DPAC; ESA/Planck Collaboration

What is an object? Sky background extraction

- Background contains mostly zodiacal light and straylight from stars and solar system bodies + cirrus clouds
- Large-scale coherence of the background. If not correctly accounted for, it can add-up systematics to galaxy fluxes / shape measurements
- But what are object edges? Sometimes it is hard to tell!



Akhlagi+15: NoiseChisel

Weak lensing: what do we need

- High accuracy on galaxy shapes
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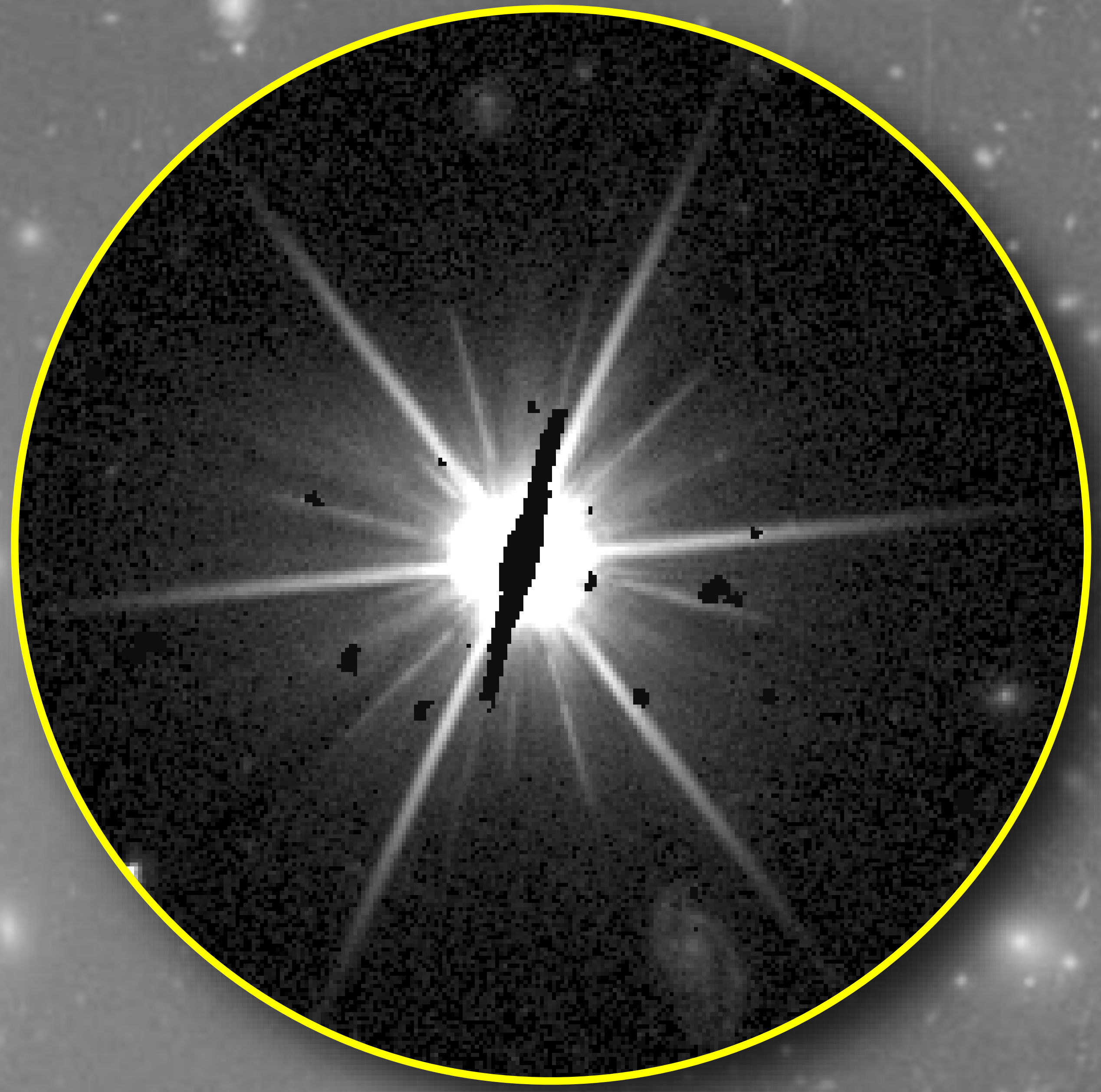
  - … Requires a robust tool to estimate shapes (in Euclid: LensMC, Euclid Collaboration: G. Congedo+24)
  - … Requires an accurate calibration of the PSF



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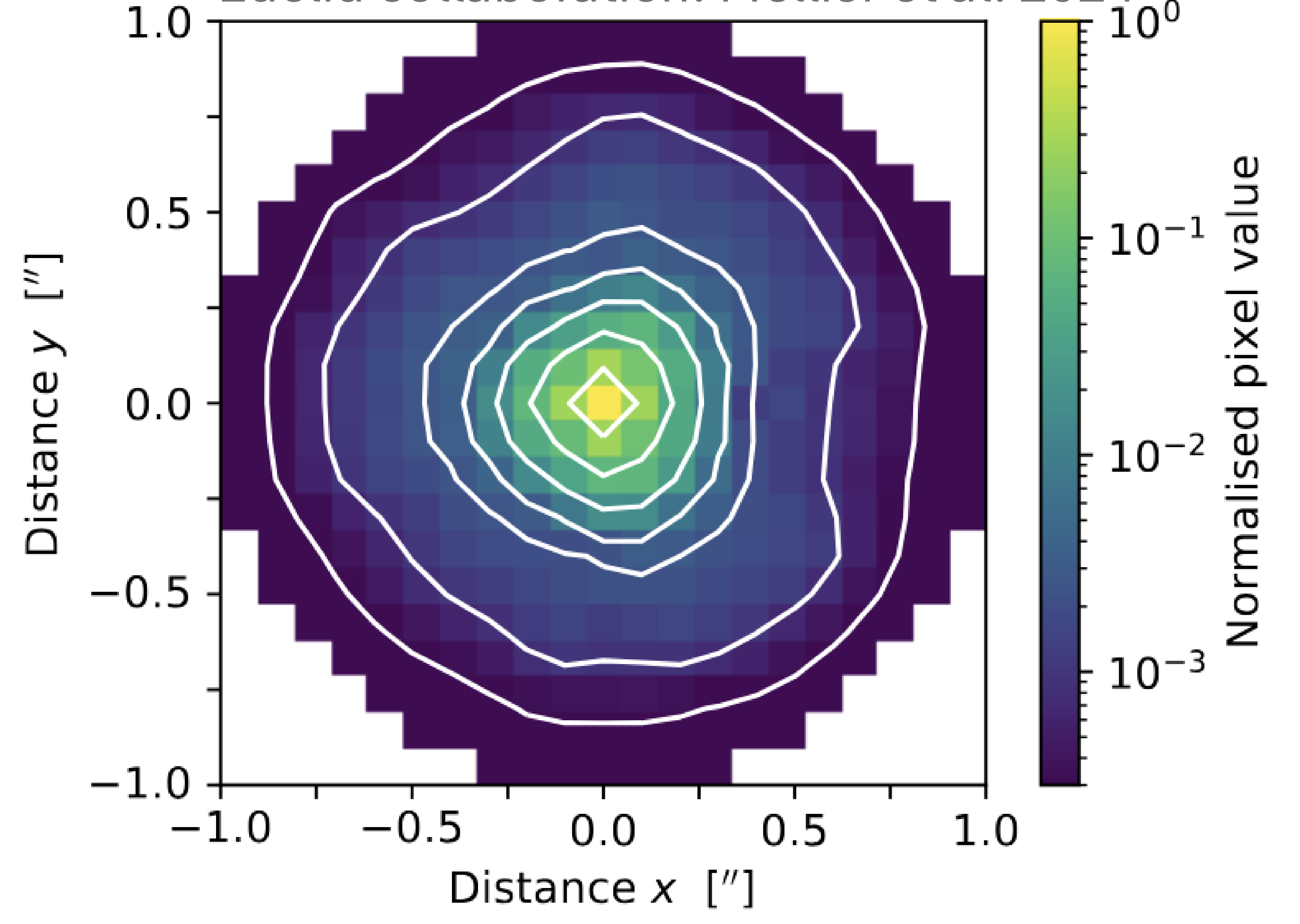
Euclid collaboration: Mellier et al. 2024



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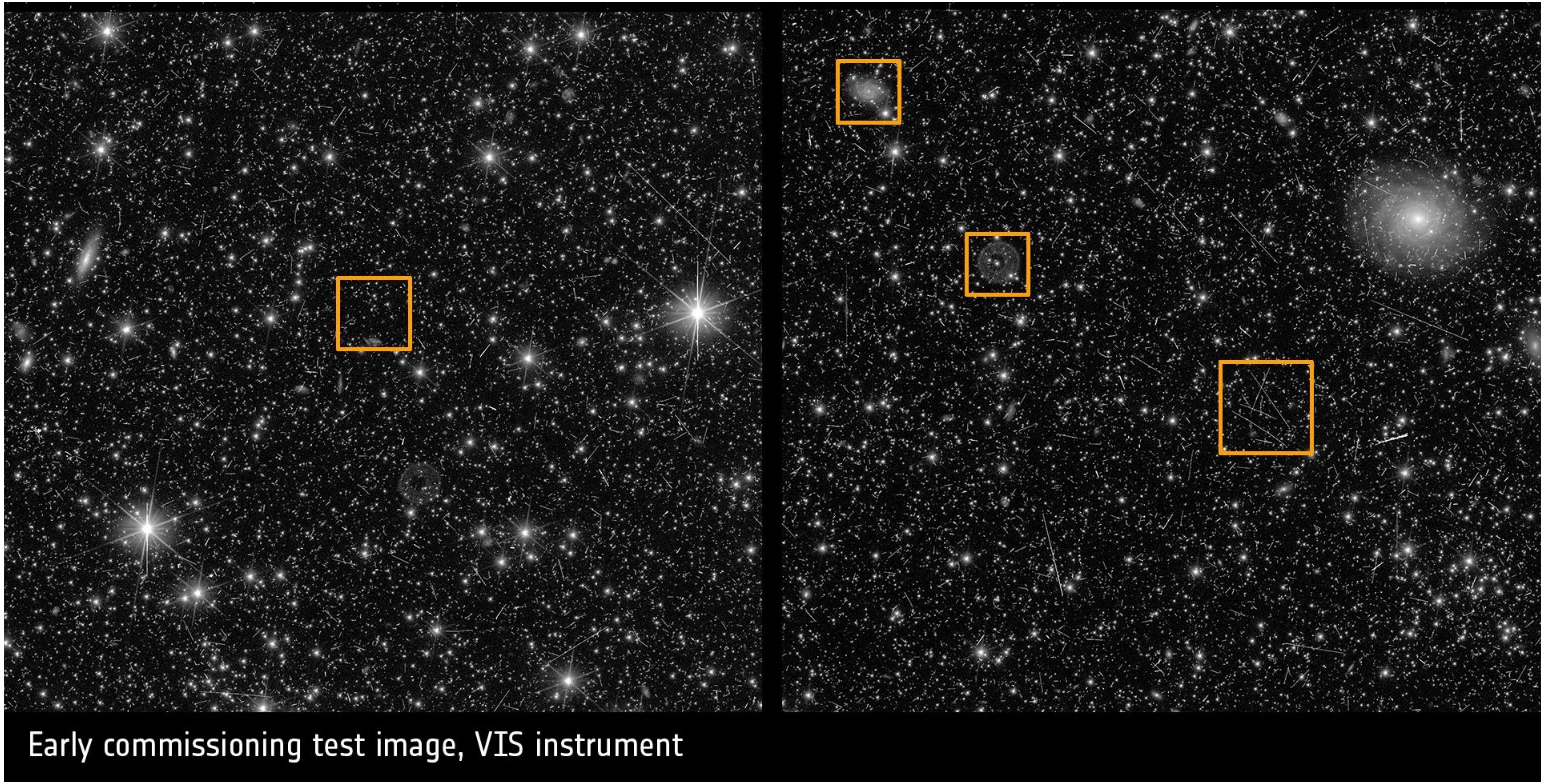
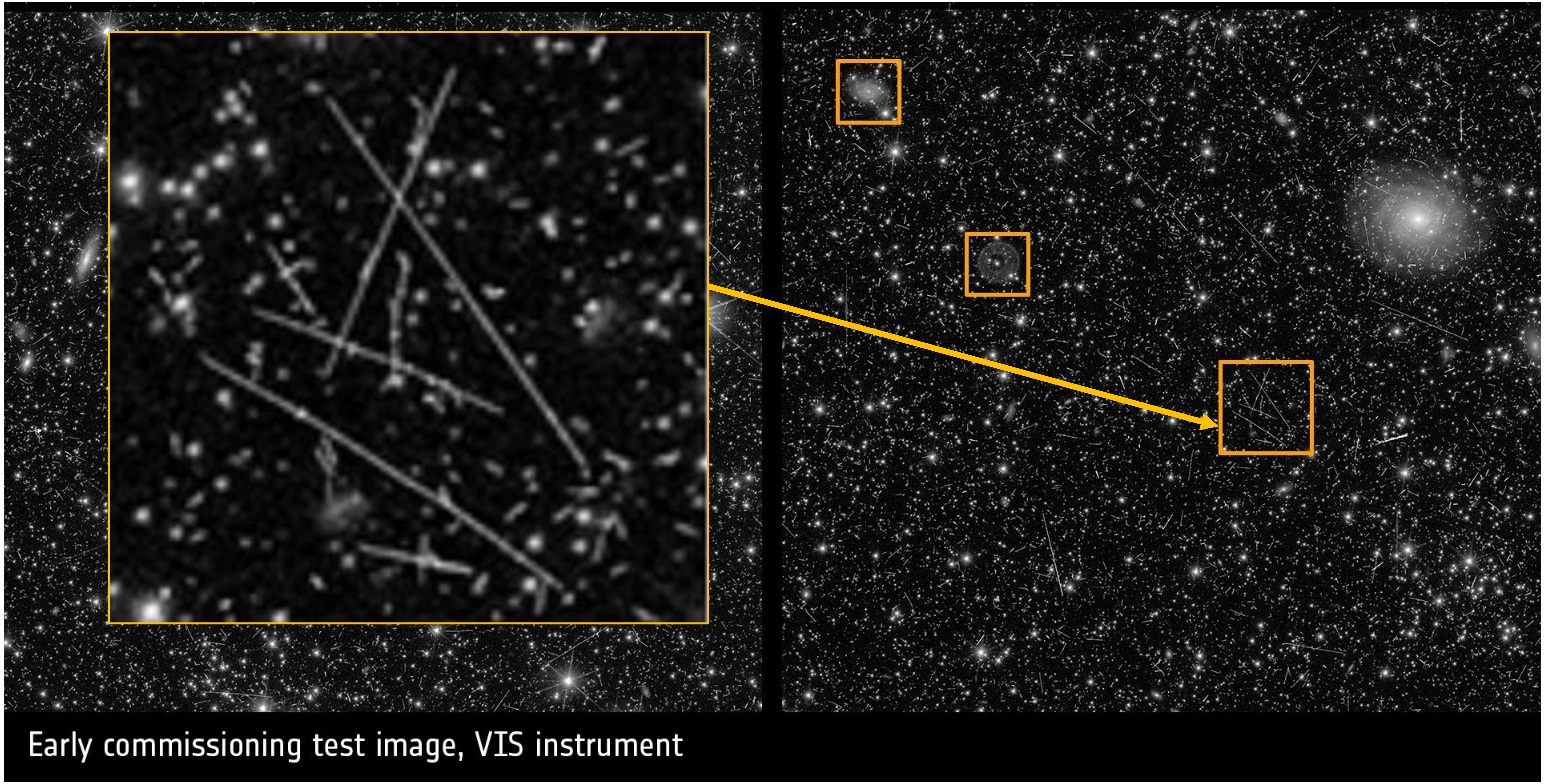
  - … Requires an accurate calibration of the PSF
  - …Requires to clean for all the effects impacting the pixels

- Reasonable measurement of galaxy fluxes
- Redshift distribution in tomographic slices

A look at Euclid first images



A look at Euclid first images

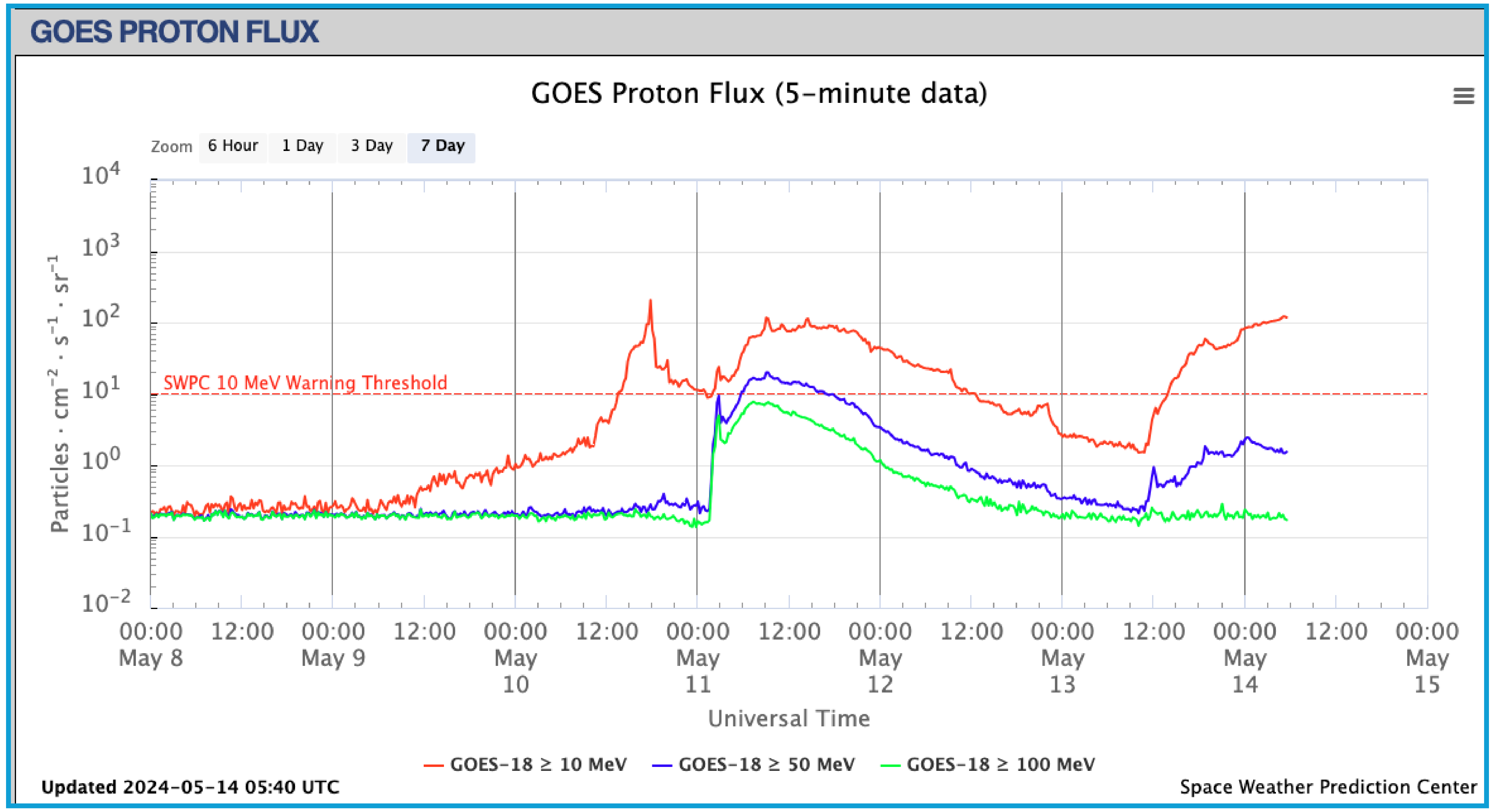


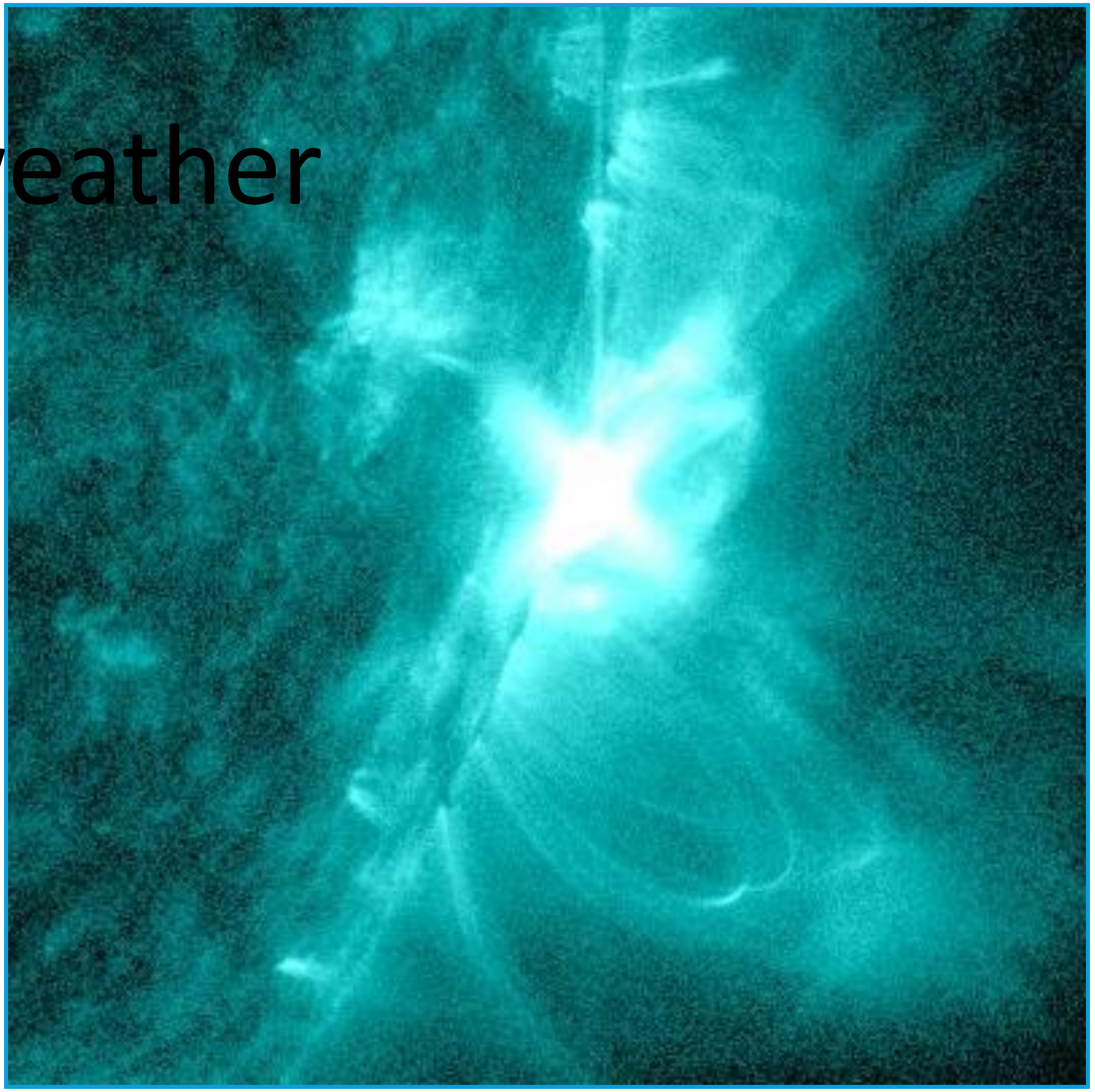
Space weather

mai 2024, Pugny-Chatenod

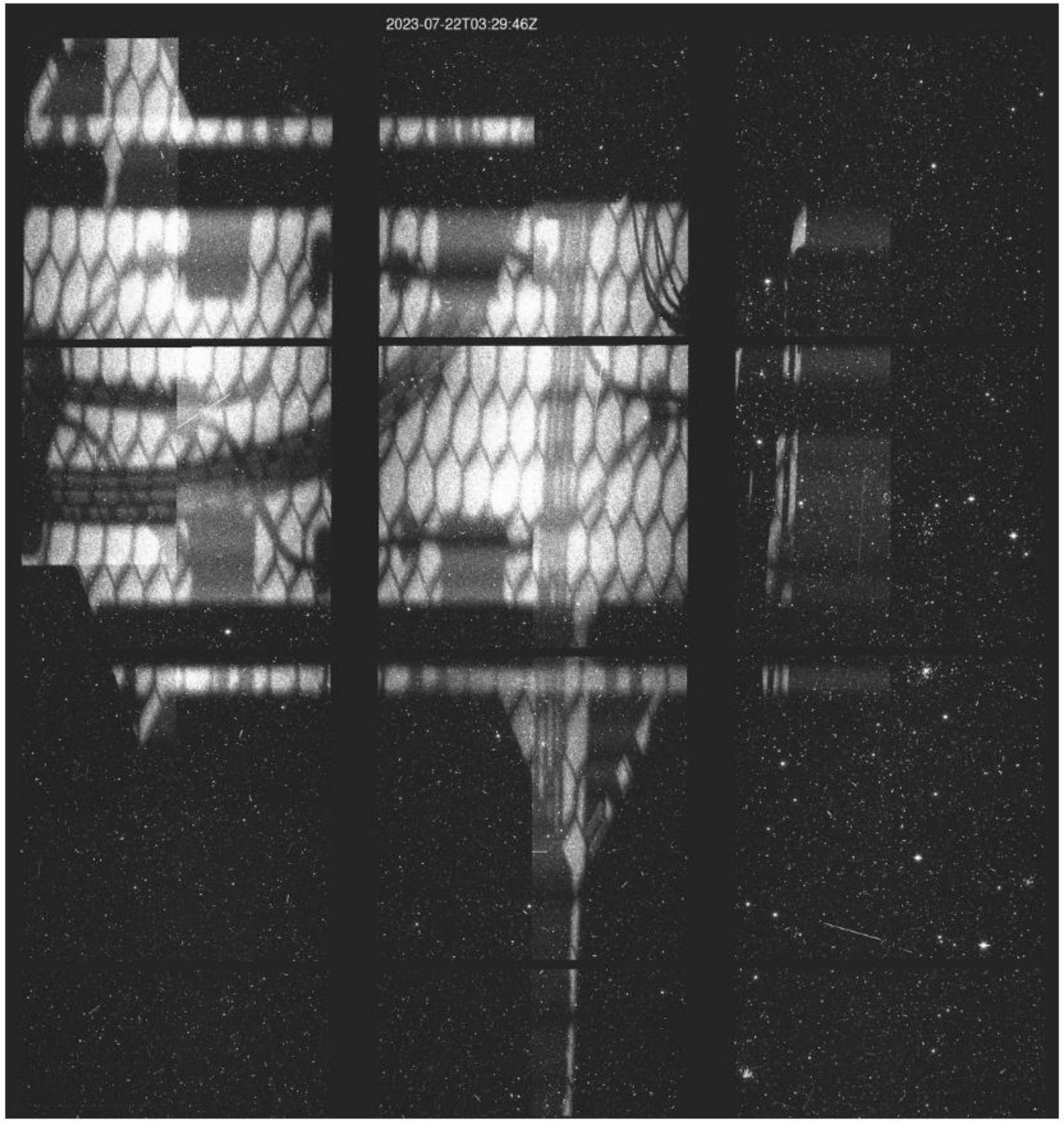
Photo Famille Bouchet Bert Manoz

Being in space means …
being sensitive to space weather





Credit: ESA/Euclid consortium / NASA



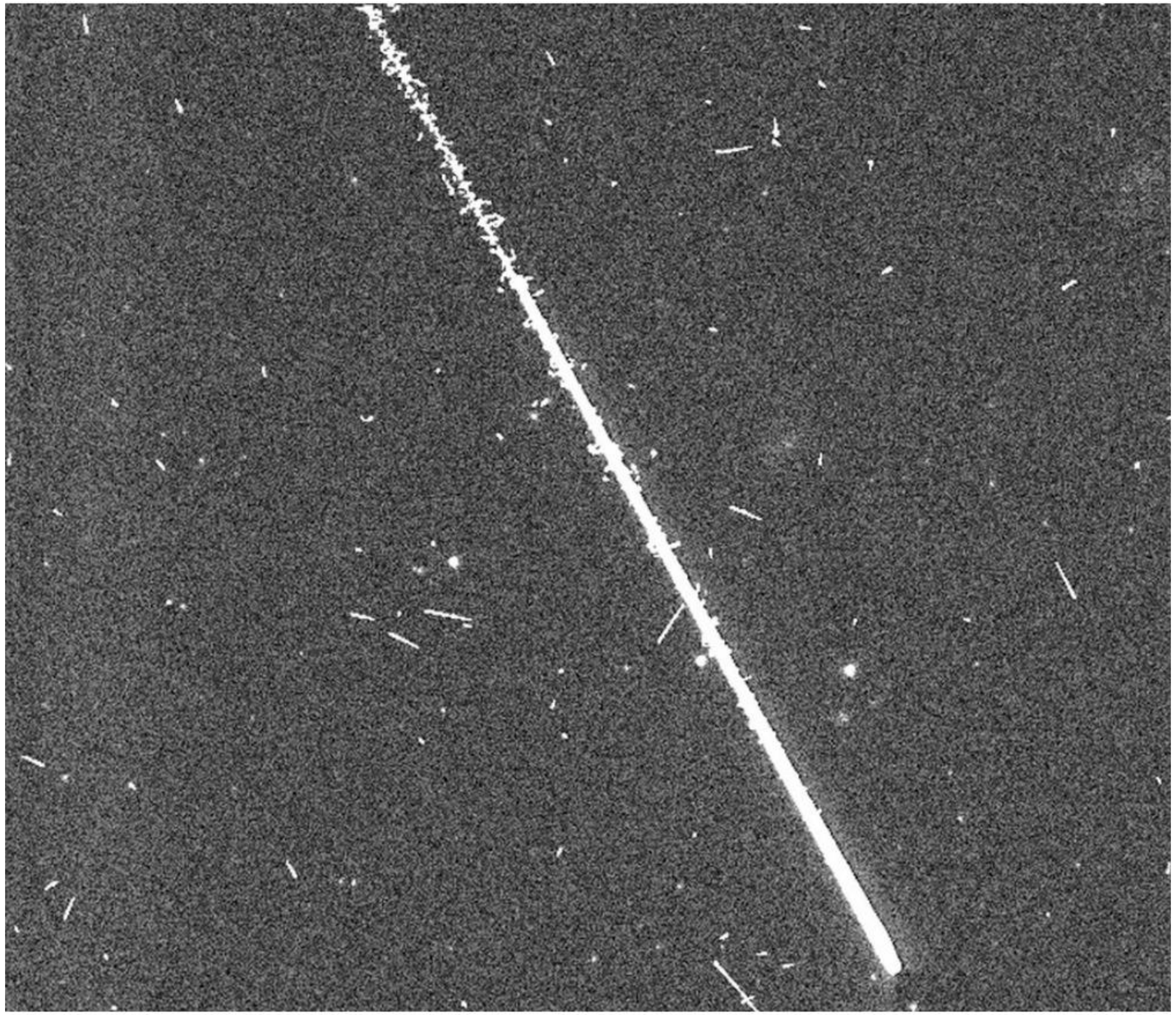
Impact on VIS images

Several kind of cosmics with different morphologies

- Electrons
- Protons
  - Long-term damage (CTI)
- Energetic Xray from solar flares
  - Comes from incomplete shielding of X-Ray (see left)
  - No long-term damage
  - <3% loss of images

Credit: ESA/Euclid consortium / NASA

Impact on VIS images



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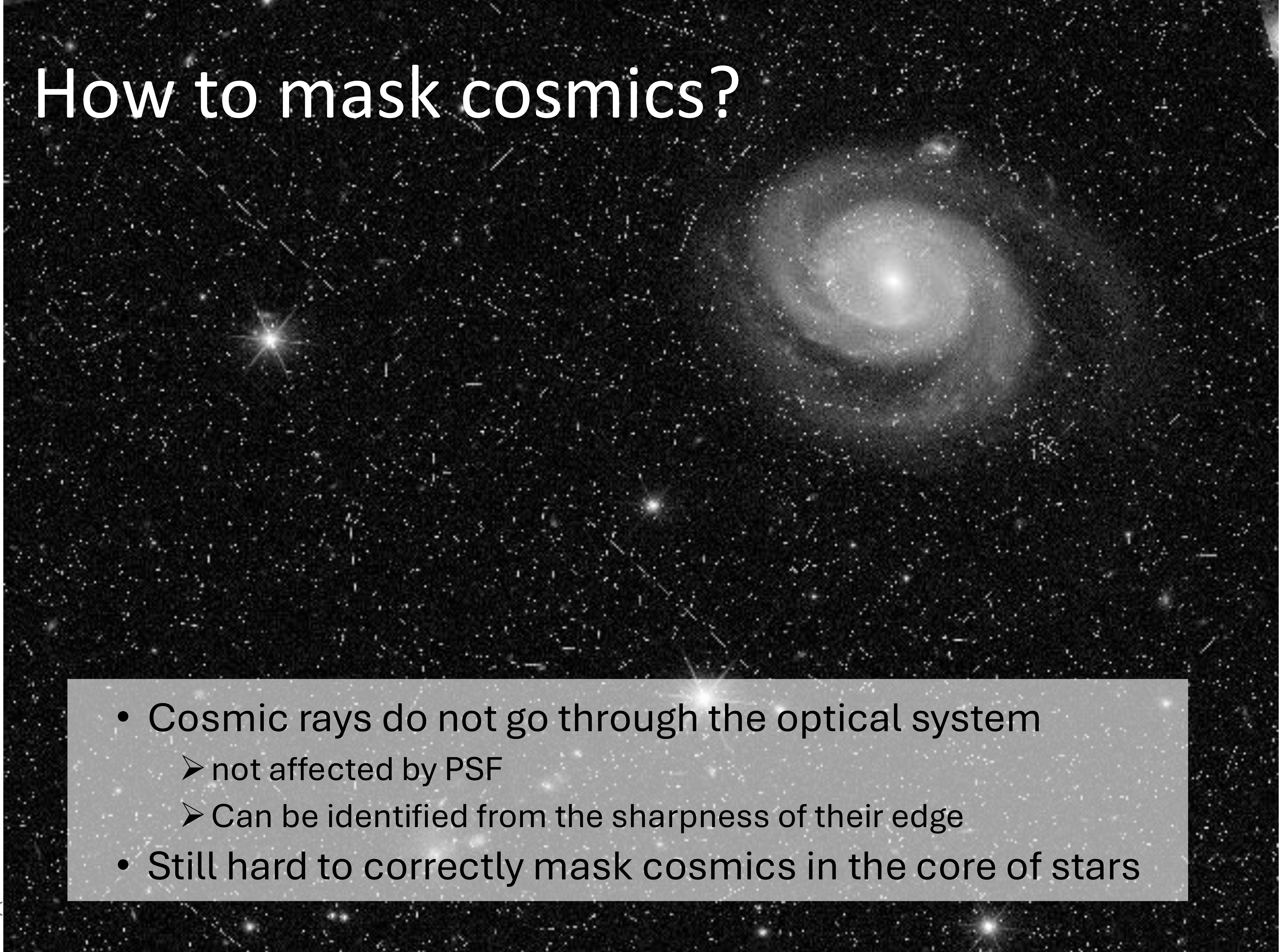
How to mask cosmics?

Euclid collaboration: Mellier et al. 2024

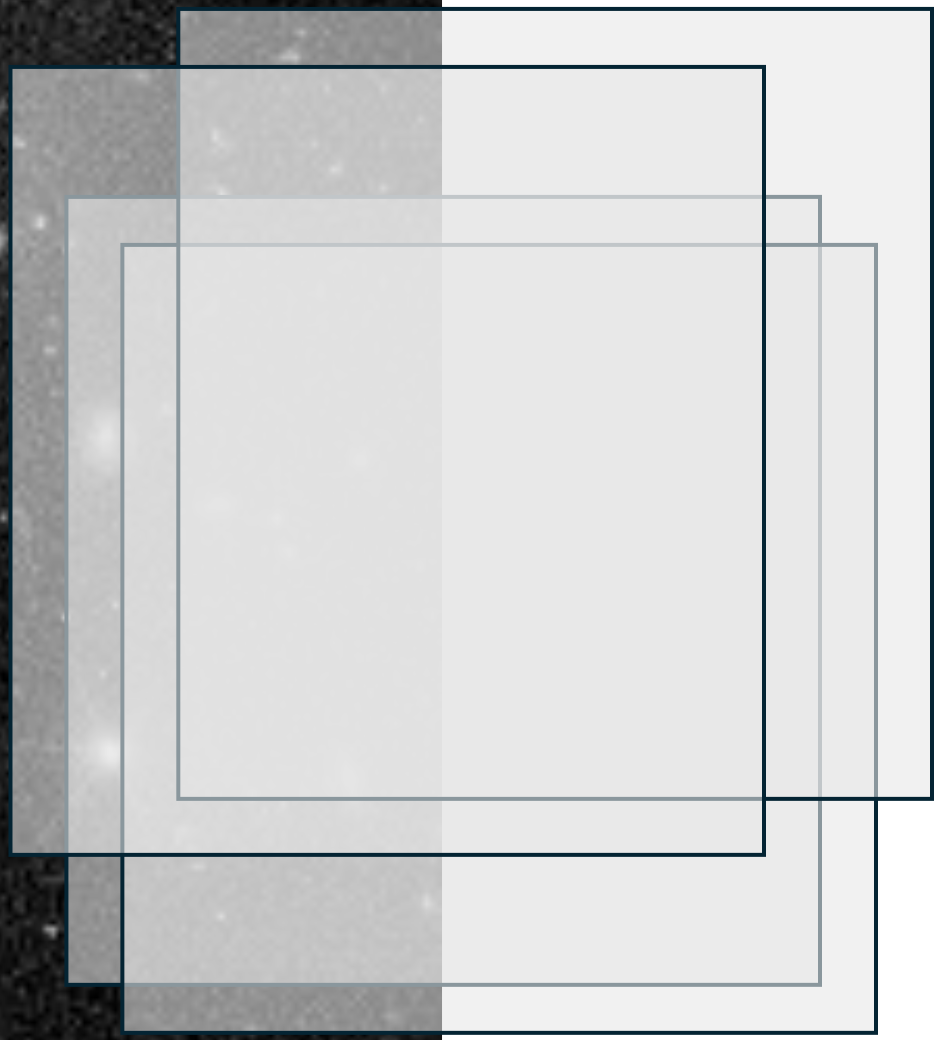
How to mask cosmics?



Euclid collaboration: Mellier et al. 2024

- Cosmic rays do not go through the optical system
  - ➢ not affected by PSF
  - ➢ Can be identified from the sharpness of their edge
- Still hard to correctly mask cosmics in the core of stars

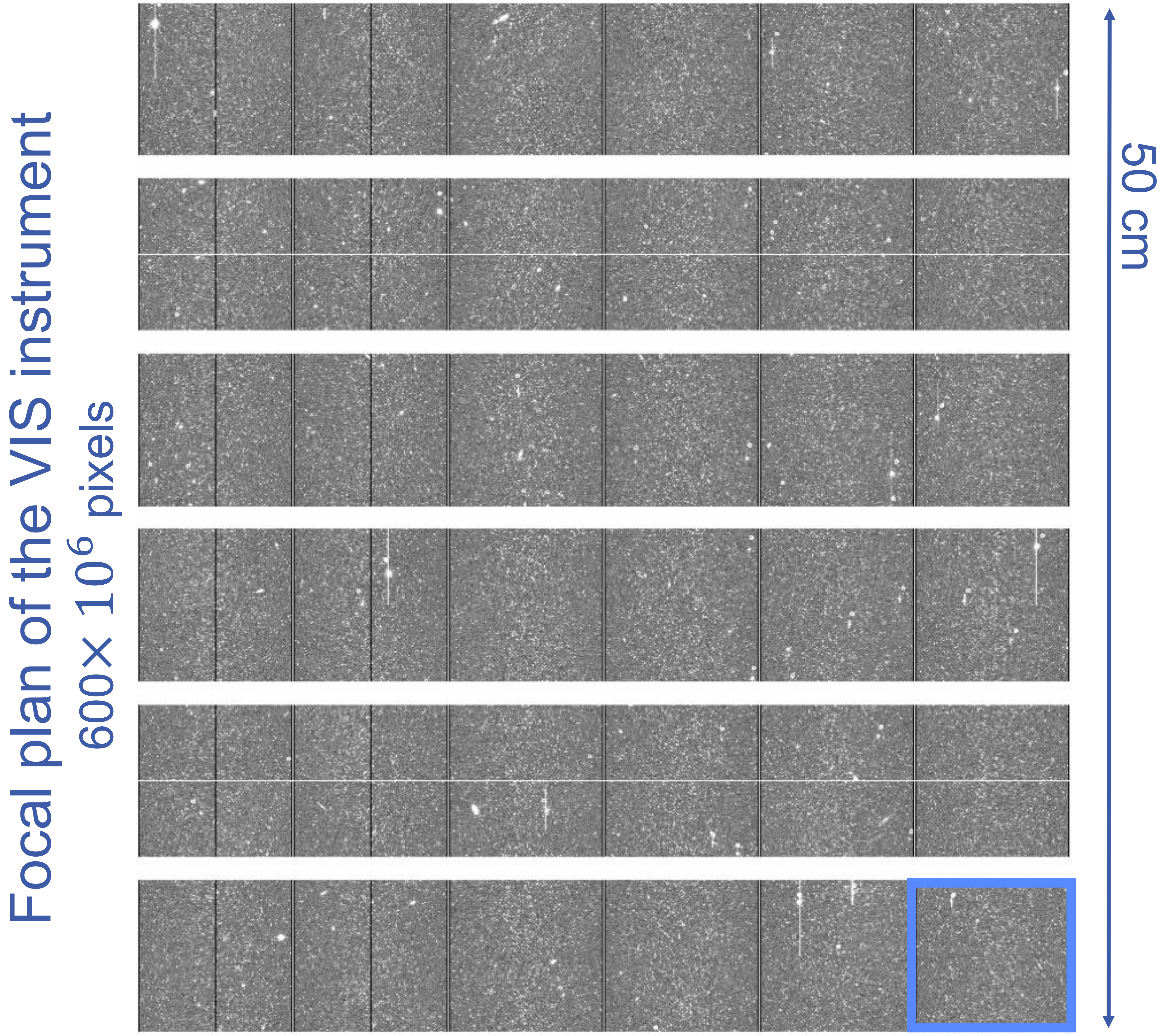
How to mask cosmics?



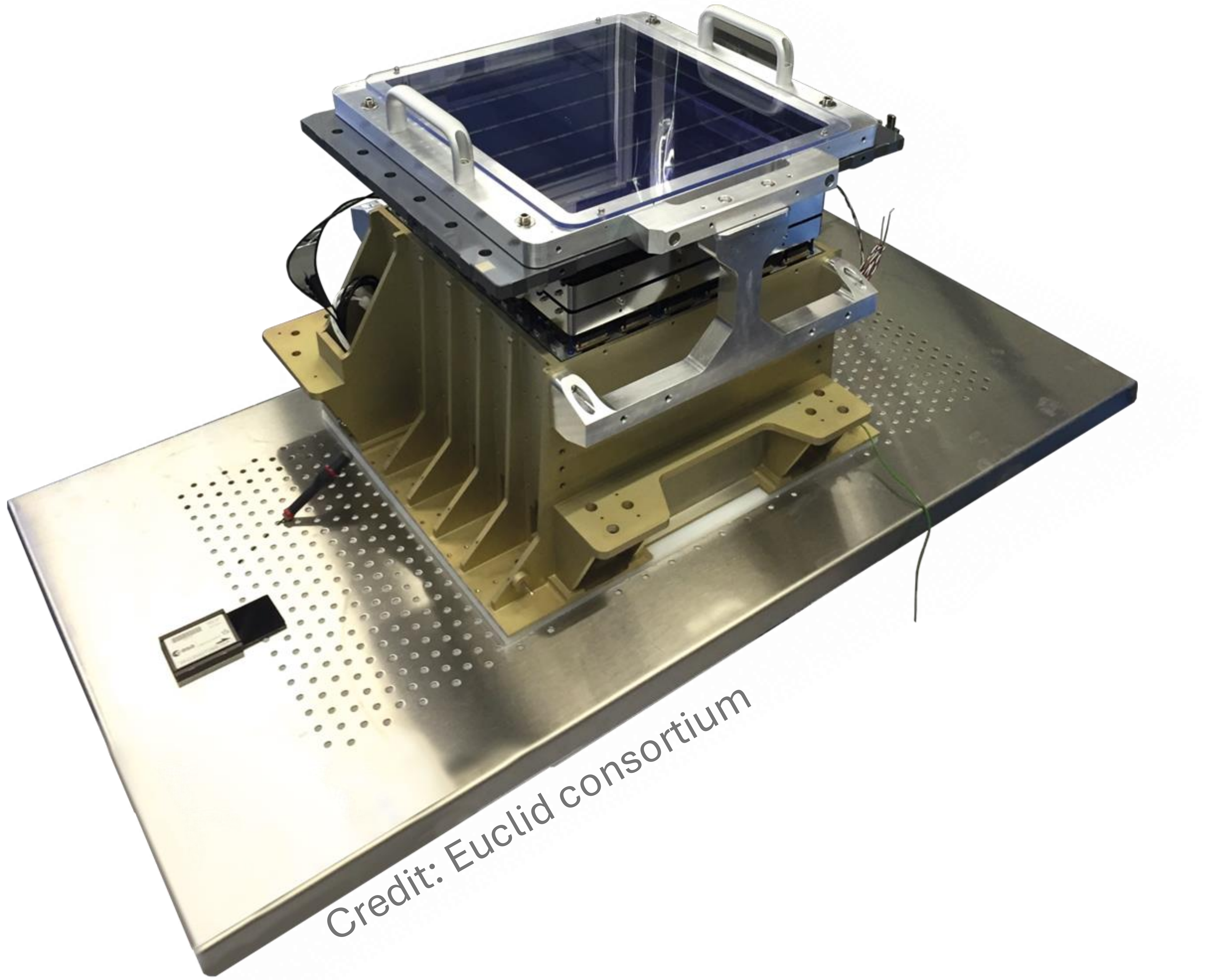
Can also be identified from the stack image
Dithering strategy: 4 nominal exposures + 2 short exposures

Euclid collaboration: Mellier et al. 2024

Overview of a data acquisition chain: VIS on Euclid



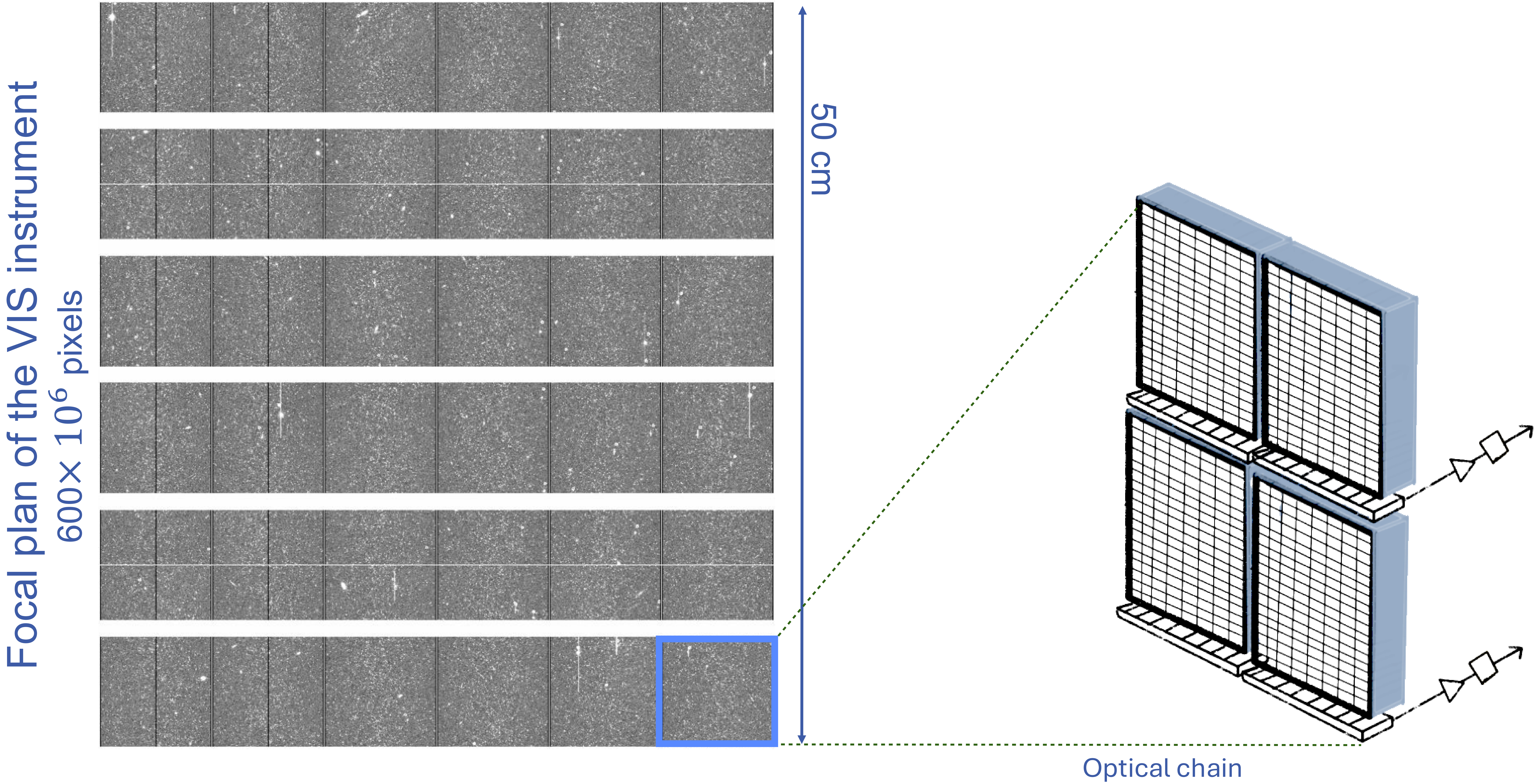
600 million pixels



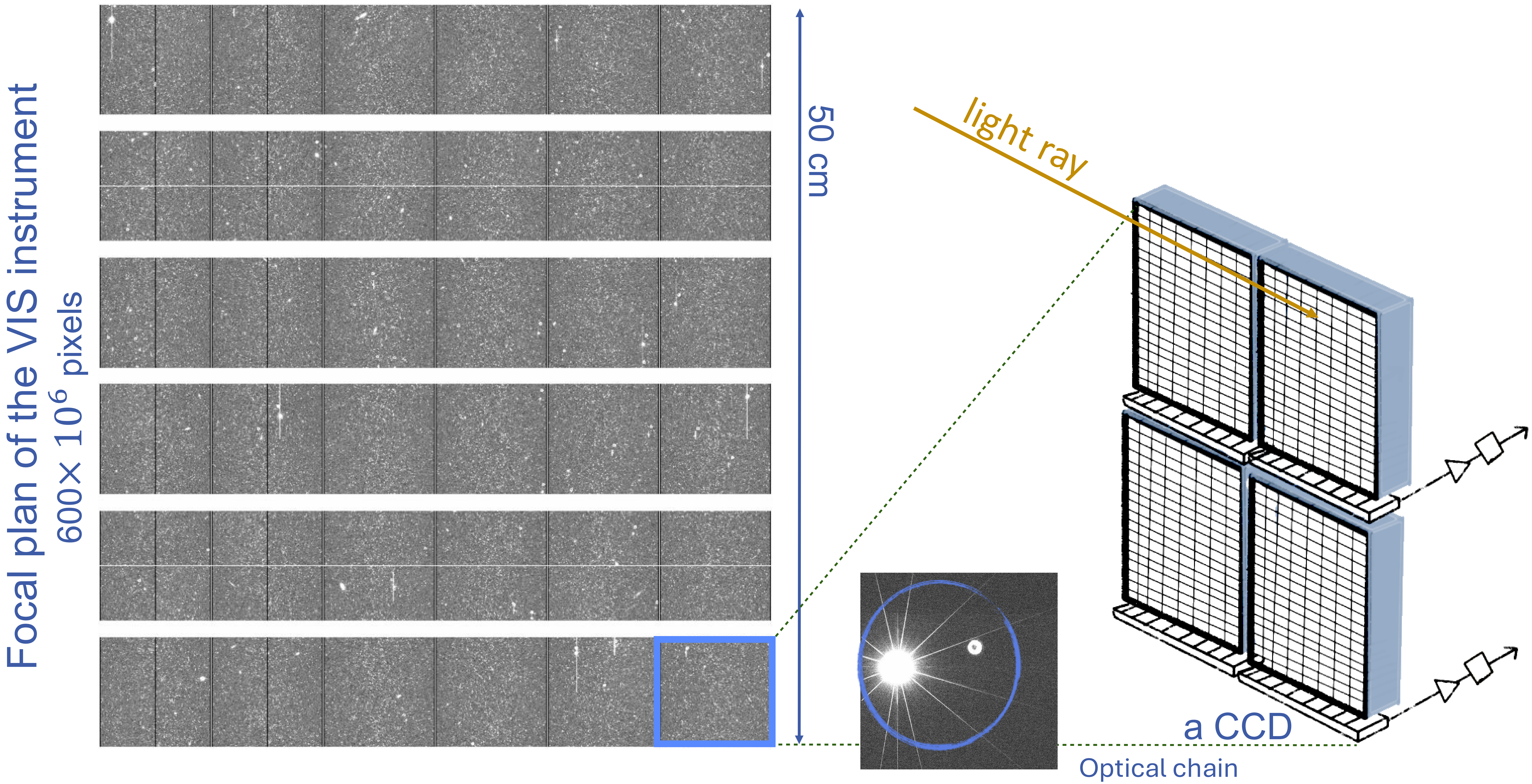
300 000 galaxies

50 000 directly useable for shape measurement

Overview of a data acquisition chain: VIS on Euclid



Overview of a data acquisition chain: VIS on Euclid



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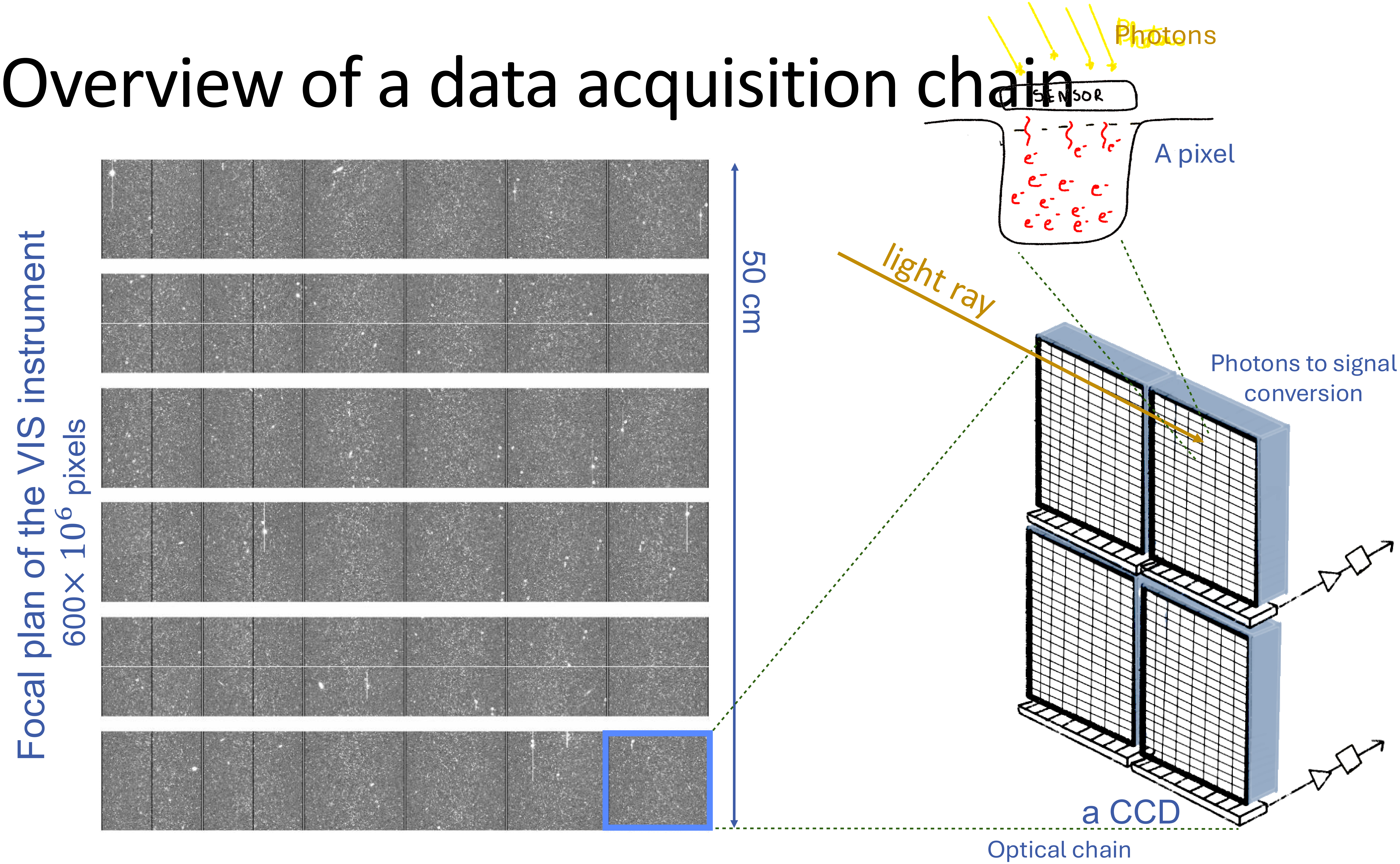
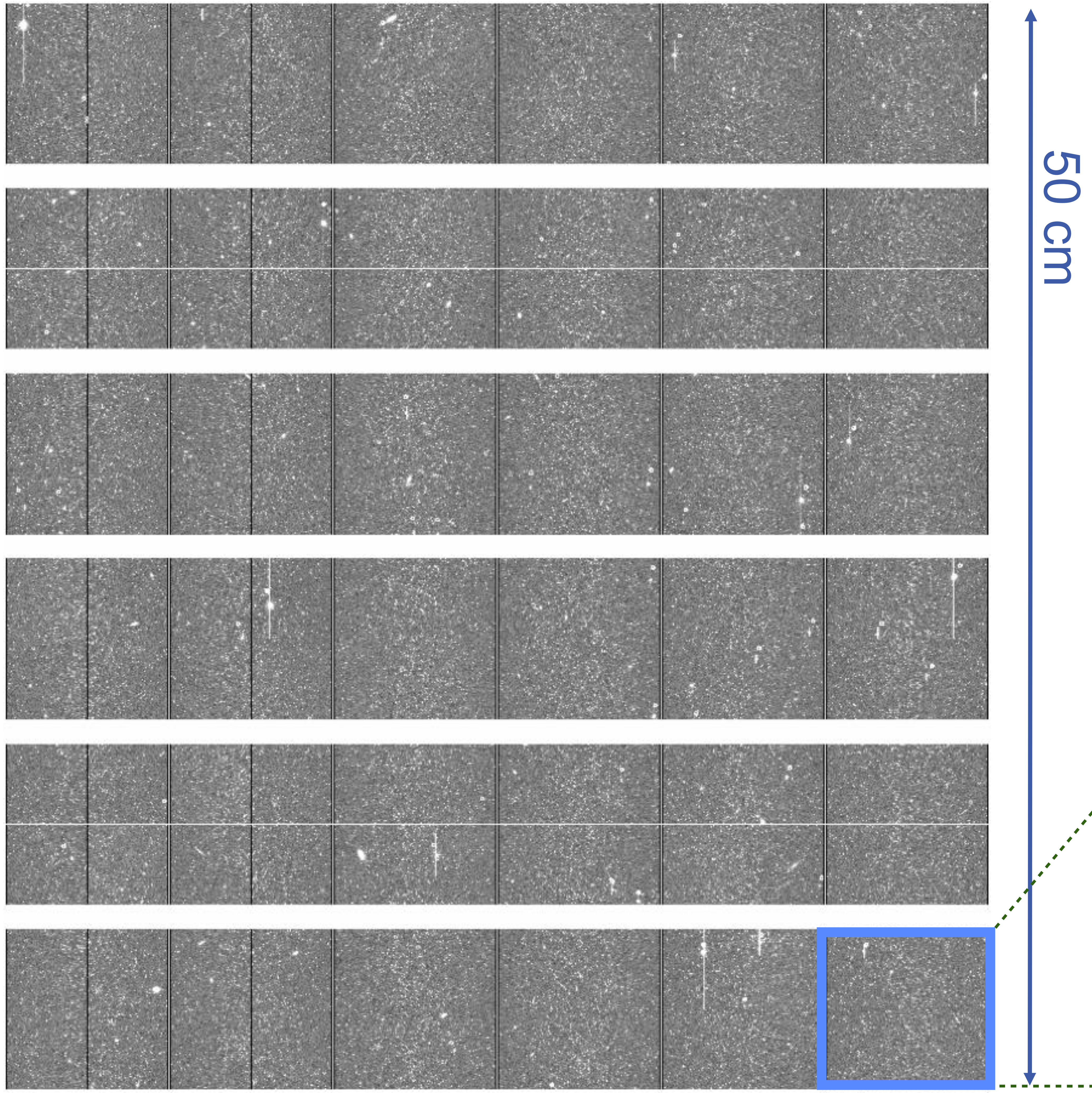
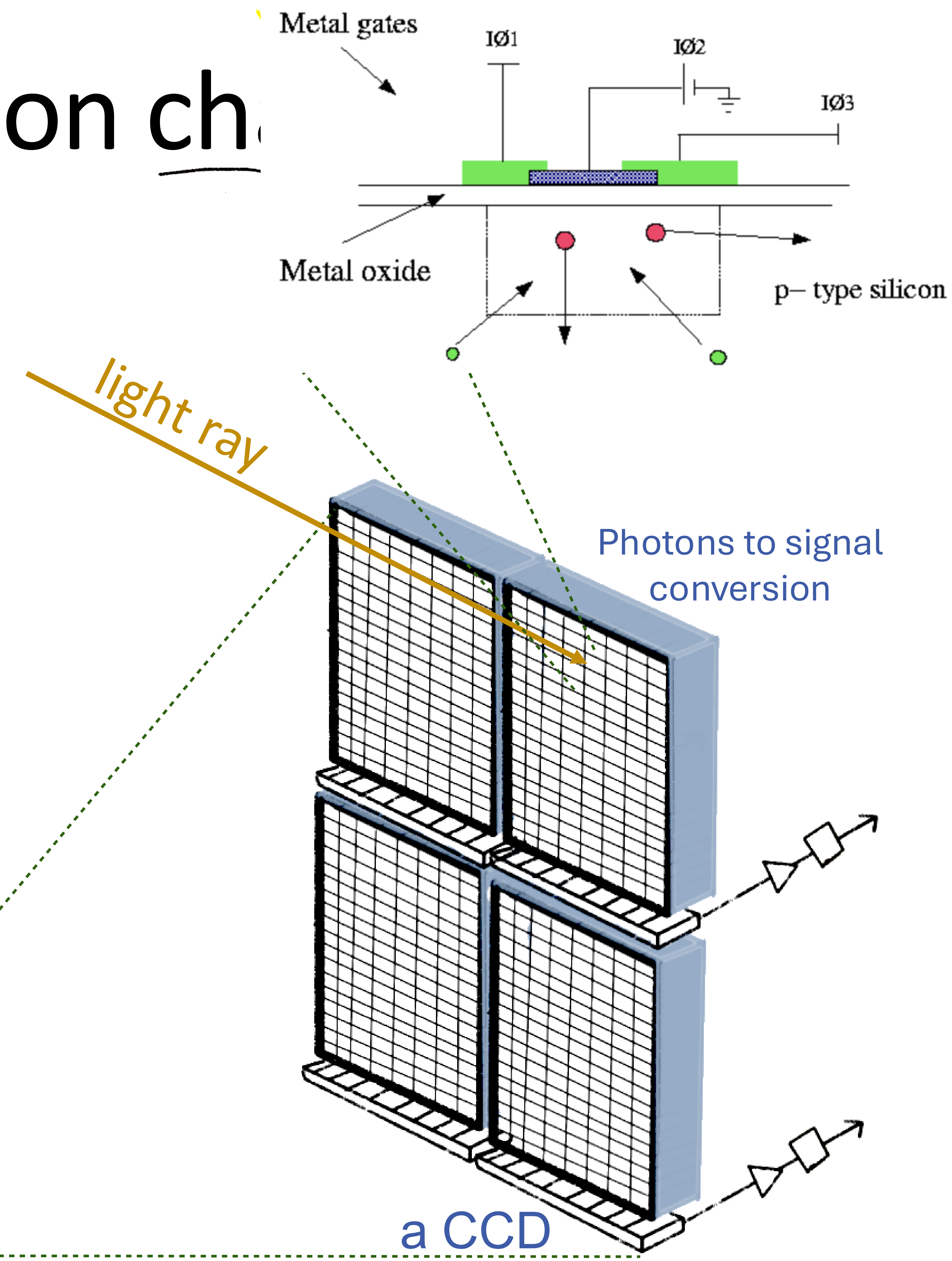


Overview of a data acquisition ch

Focal plan of the VIS instrument
600×10^6 pixels





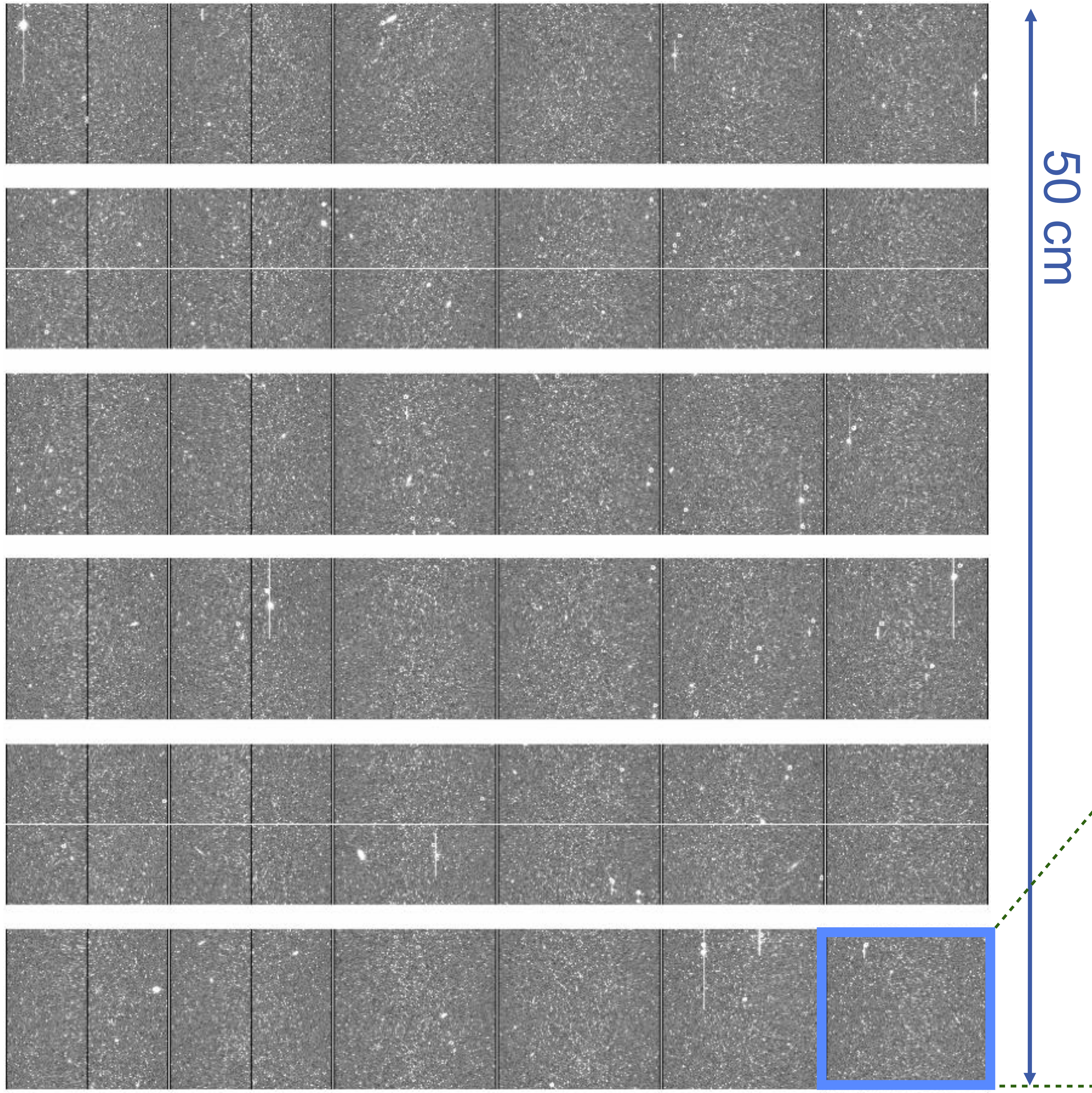
Optical chain

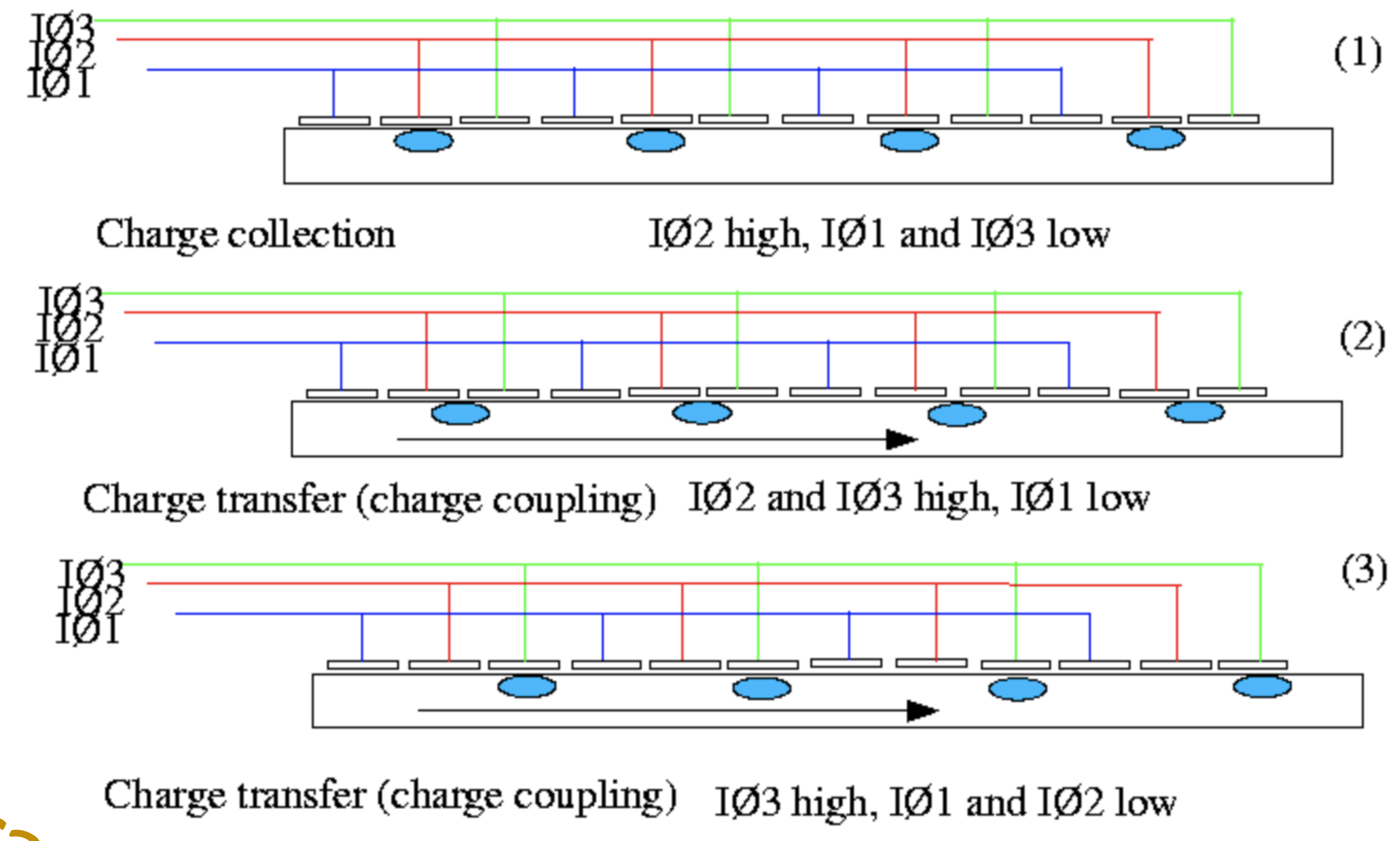
https://www.mssl.ucl.ac.uk

Overview of a data acquisition c

Focal plan of the VIS instrument

600×10^6 pixels





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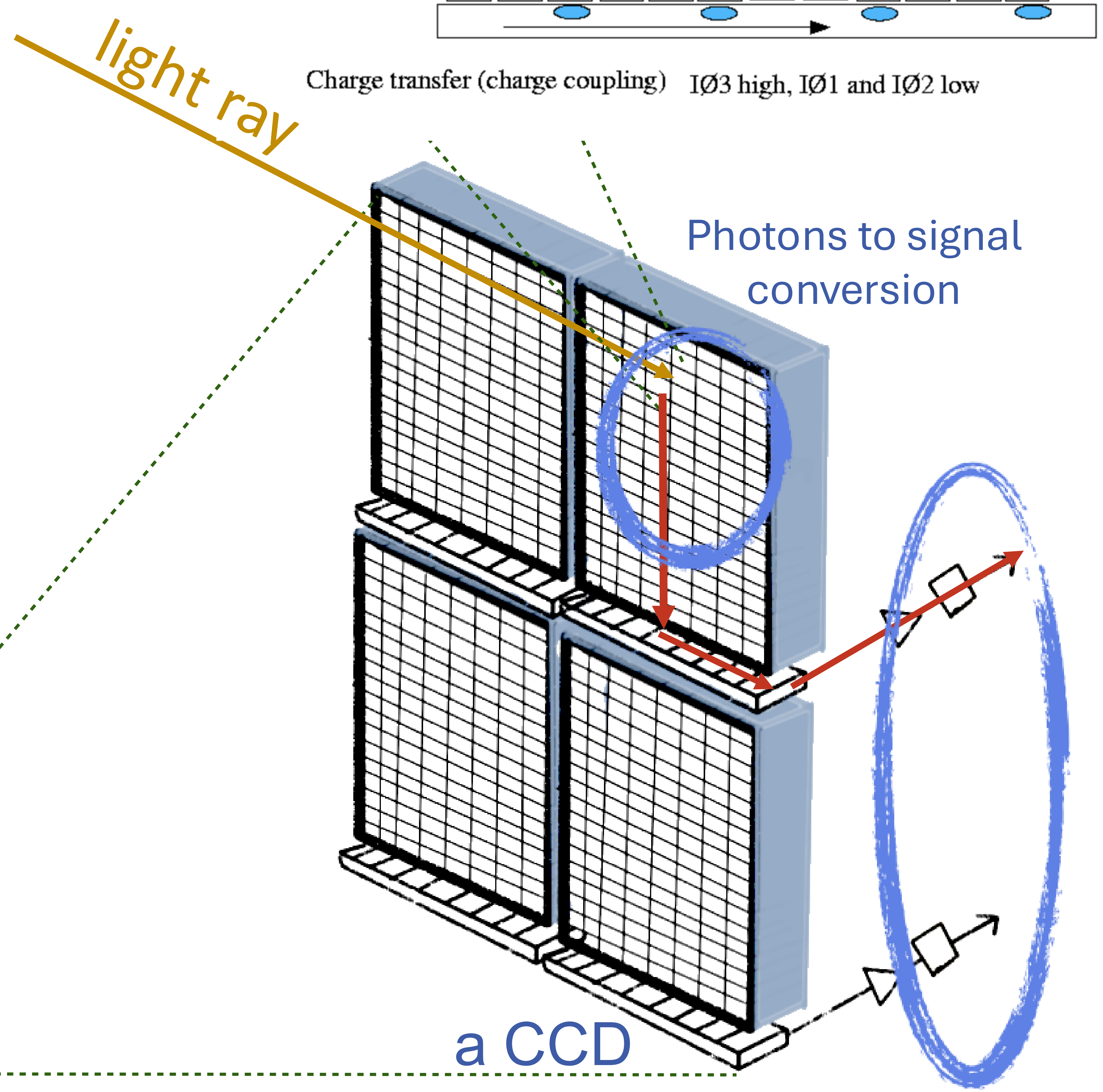
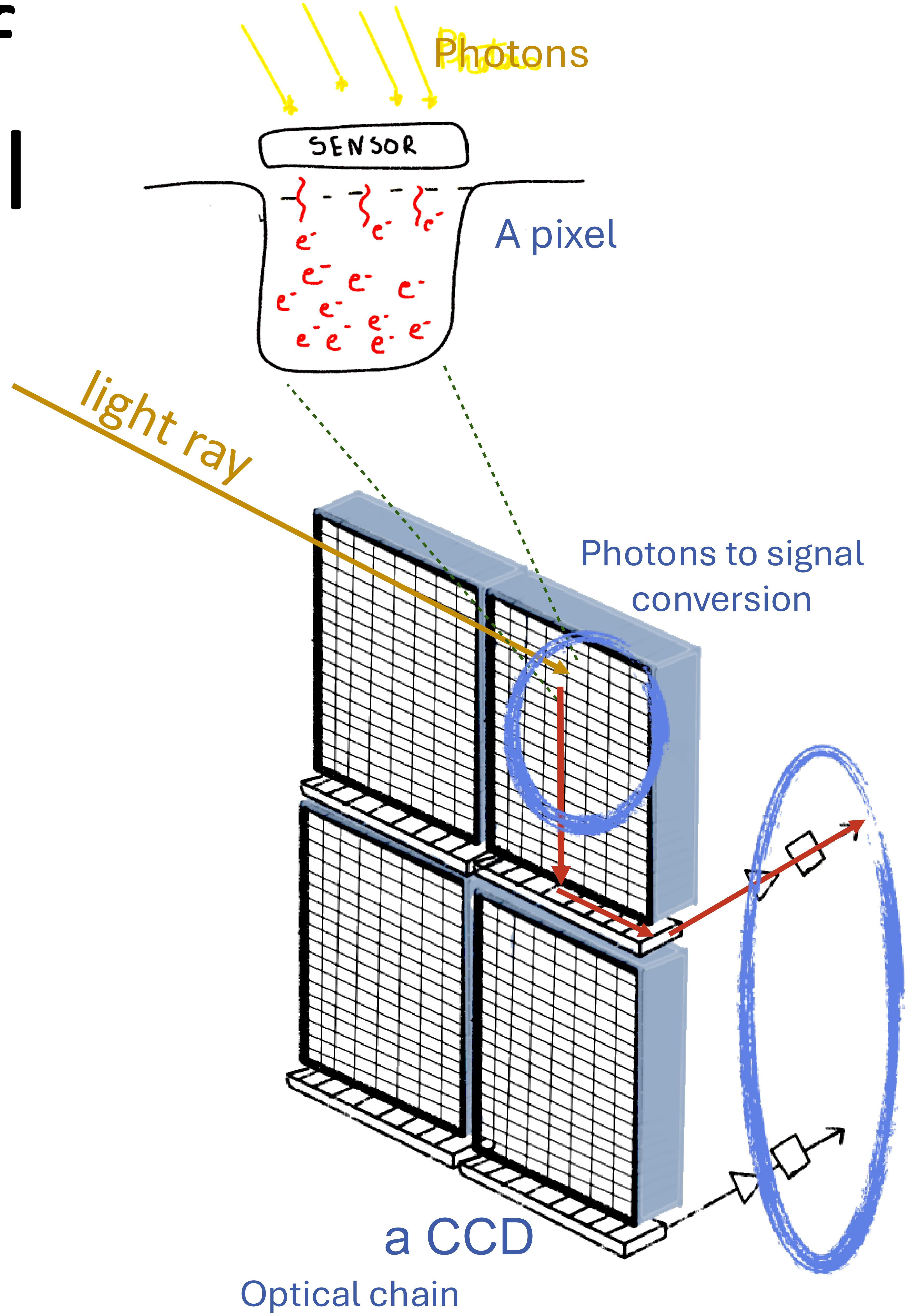


Optical chain

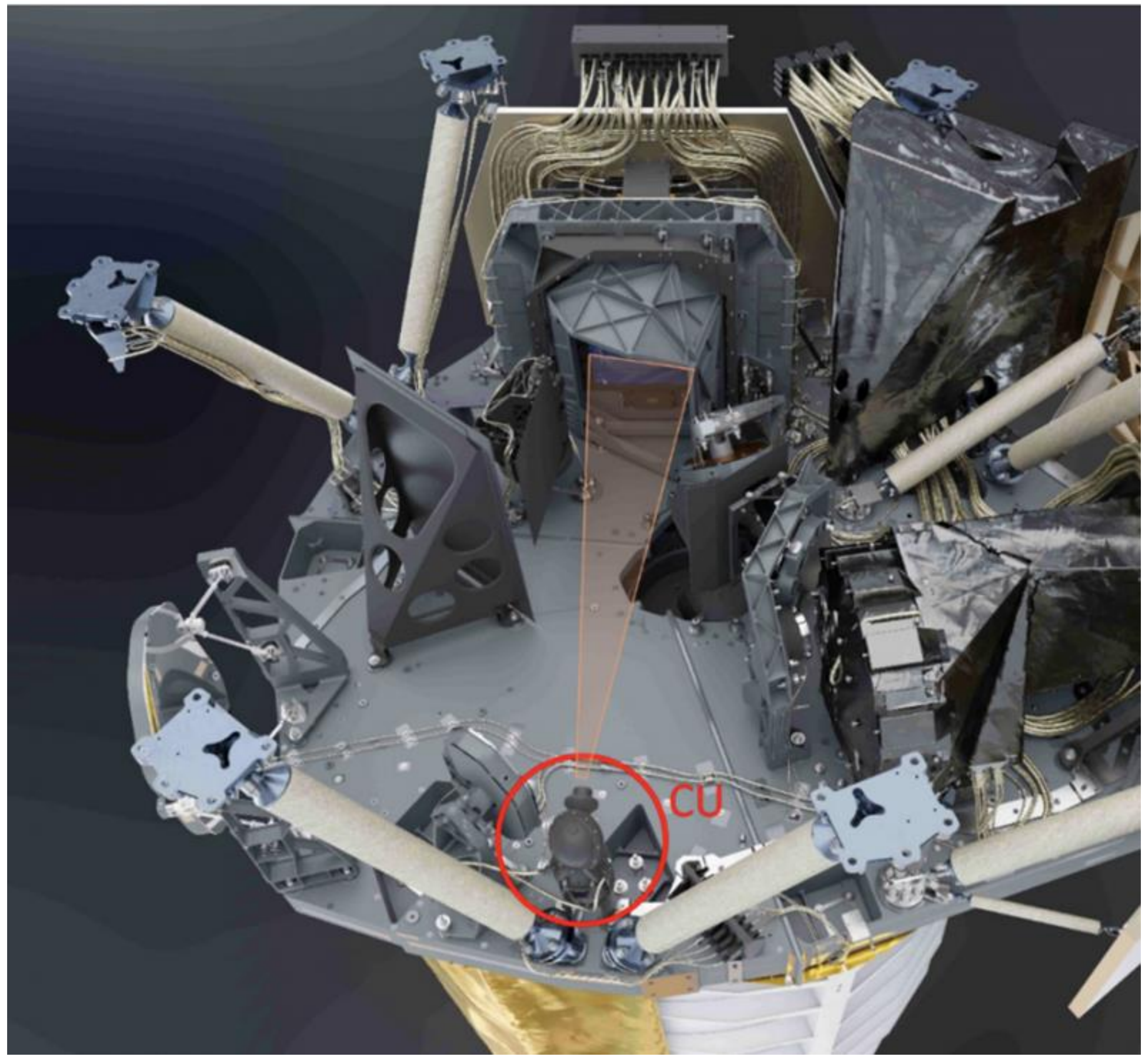
How to quantify the impact of electronics / optics at the pixel level?

- We take calibration exposures
- It is a significant amount of telescope time!

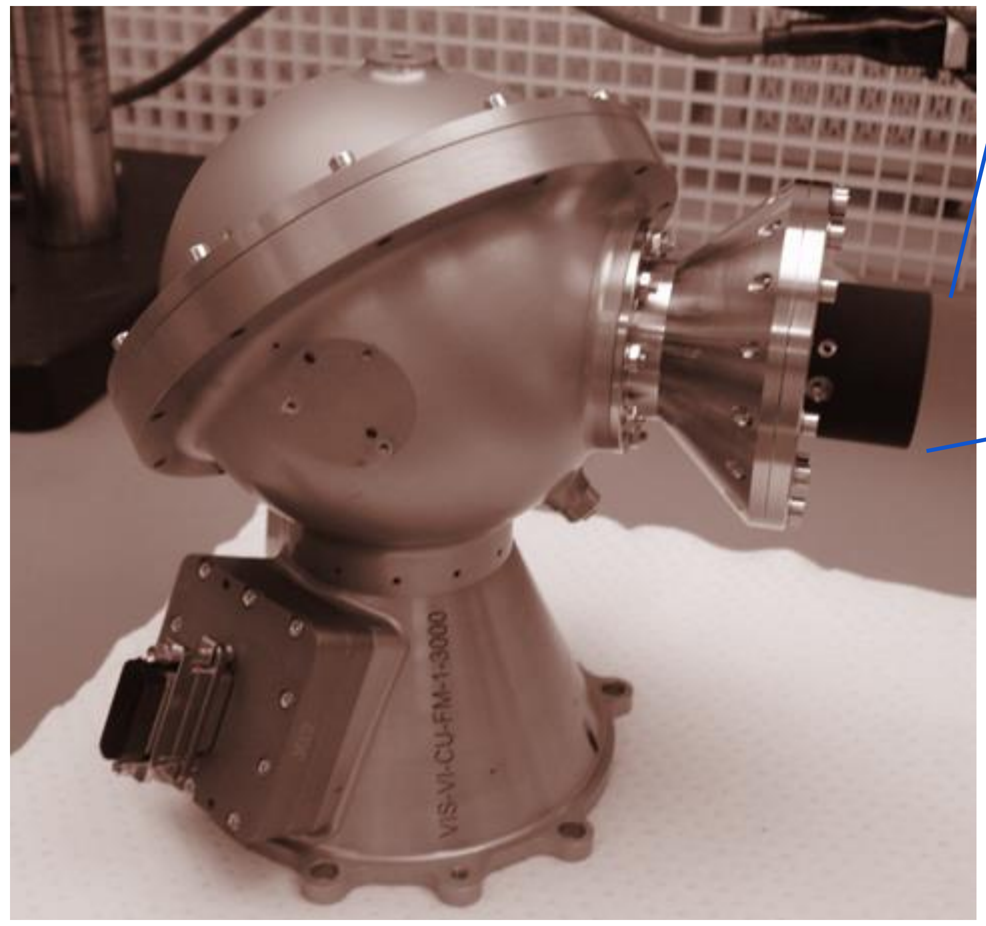
VIS	
4 I_E-band nominal exposures	566 s each
2 I_E-band short exposures	95 s each
Bias	2 per day
Dark	4 per day
Flat	6 per day
Trap pumping	6 per day
Charge injection	8 per day
NISP	
4 red-grism spectro exposures	574 s each
4 Y_E-band exposures	112 s each
4 J_E-band exposures	112 s each
4 H_E-band exposures	112 s each
1 Dark	112 s



What happens when illuminating the FPA with the calibration lamp?



https://www.ias.u-psud.fr/fr/activites-techniques/service-optique/euclid

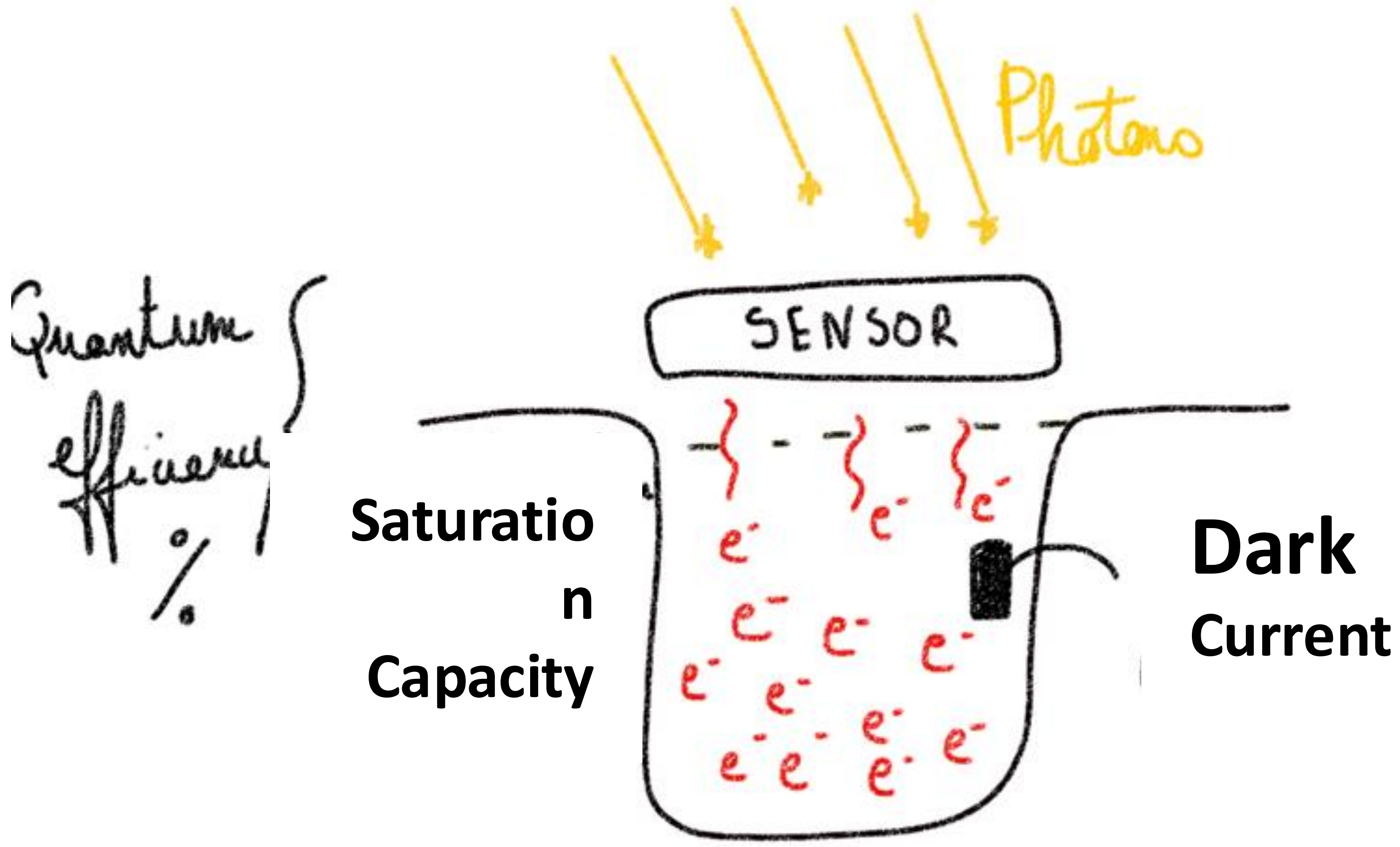


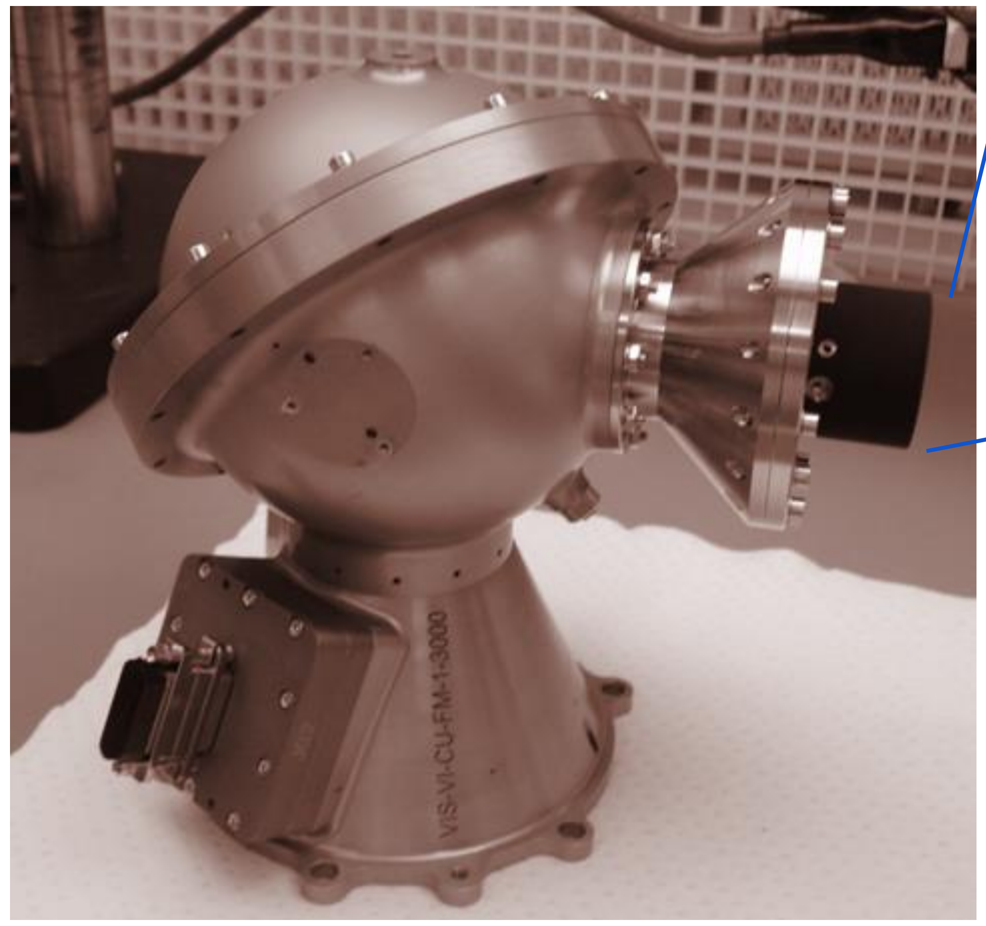
This is a calibration exposure

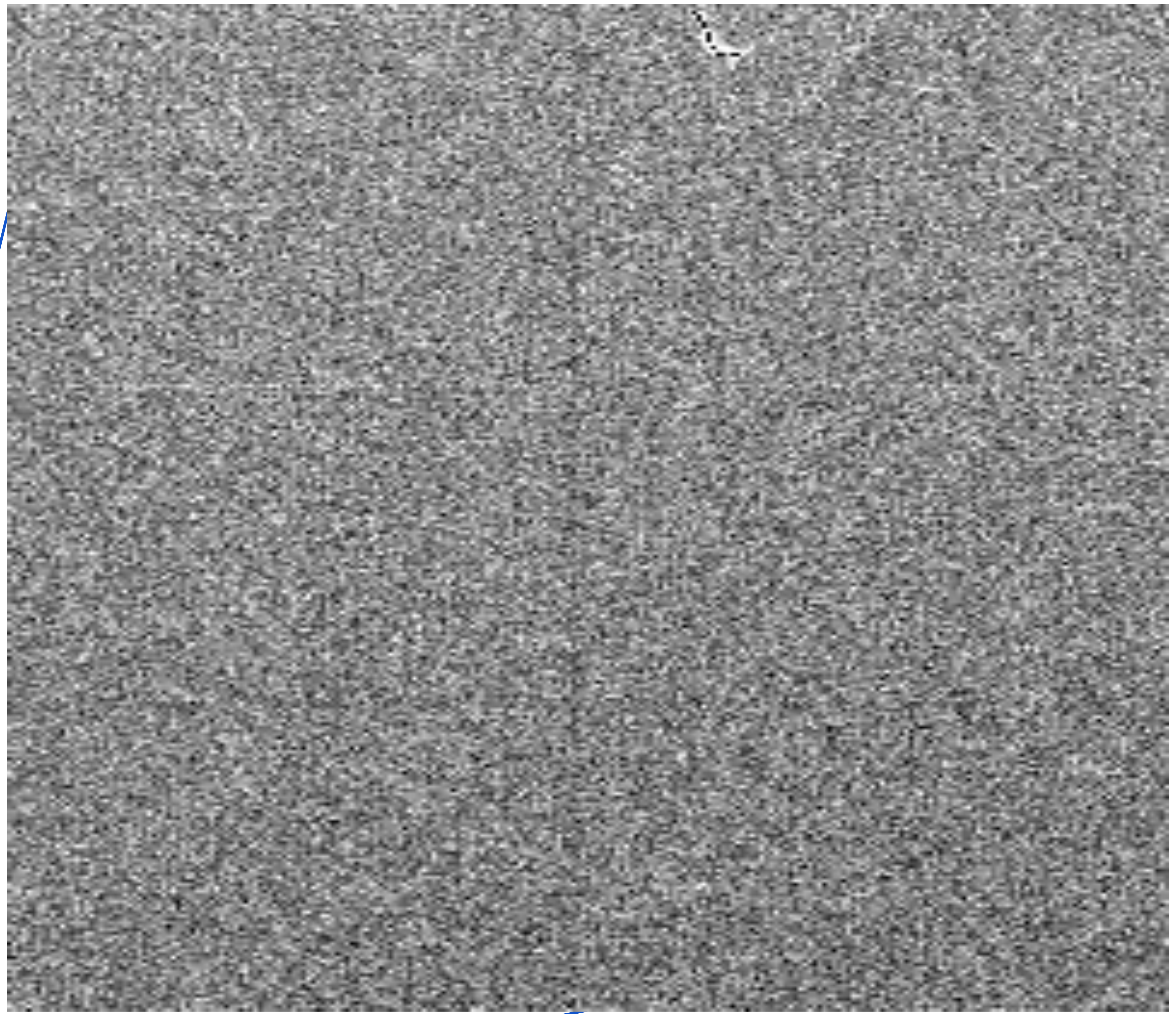
What happens when illuminating the FPA with the calibration lamp?

Flat-fields are crucial for calibration:

- **PRNU** (small-scale variations, wavelength dependent)
- **Dark pixels** (from master flats)
- **Gain** (from variance in pairs of flat-fields)
- **Non-linearity** (as a complementary dataset)
- **CTI**
- **Bright-fatter** (correlation in pairs of flat-fields)







This is a calibration exposure

Brighter-Fatter effect

The response of a given pixel to illumination is independent of the content of the neighboring pixels.

Brighter-Fatter effect

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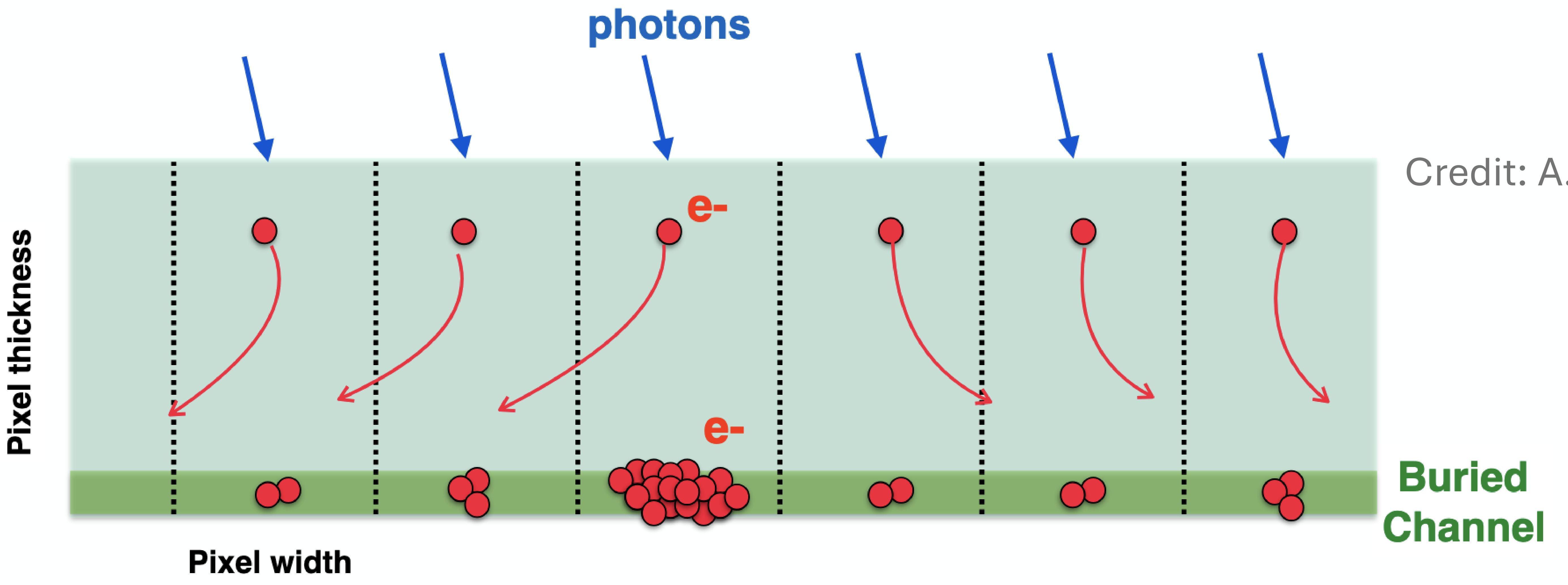
Brighter-Fatter effect

The response of a given pixel to illumination is independent of the content of the neighboring pixels.

CAUSE:
Coulomb forces induced by stored charges in a pixel deflect forthcoming charges

- → "Sharing of charge" between pixels (but total charges are conserved)
- → Change of "sharing of charge" between neighboring pixels as charge build up in the pixels
- → The details of this "sharing of charge" depends on manufacturing details of the CCD



Credit: A. Guyonnet

Brighter-Fatter effect

The response of a given pixel to illumination is ~~in~~dependent of the content of the neighboring pixels.

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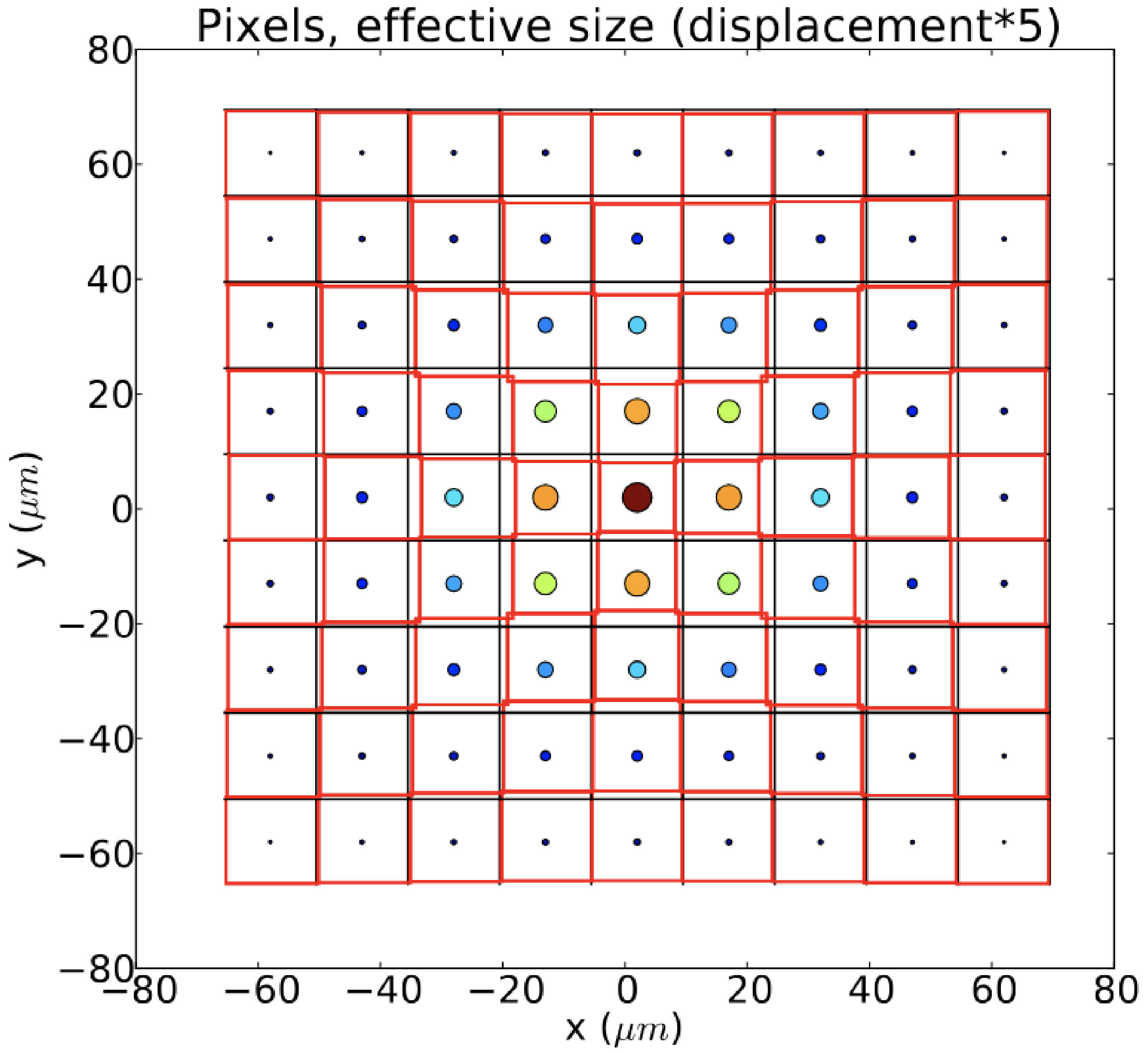
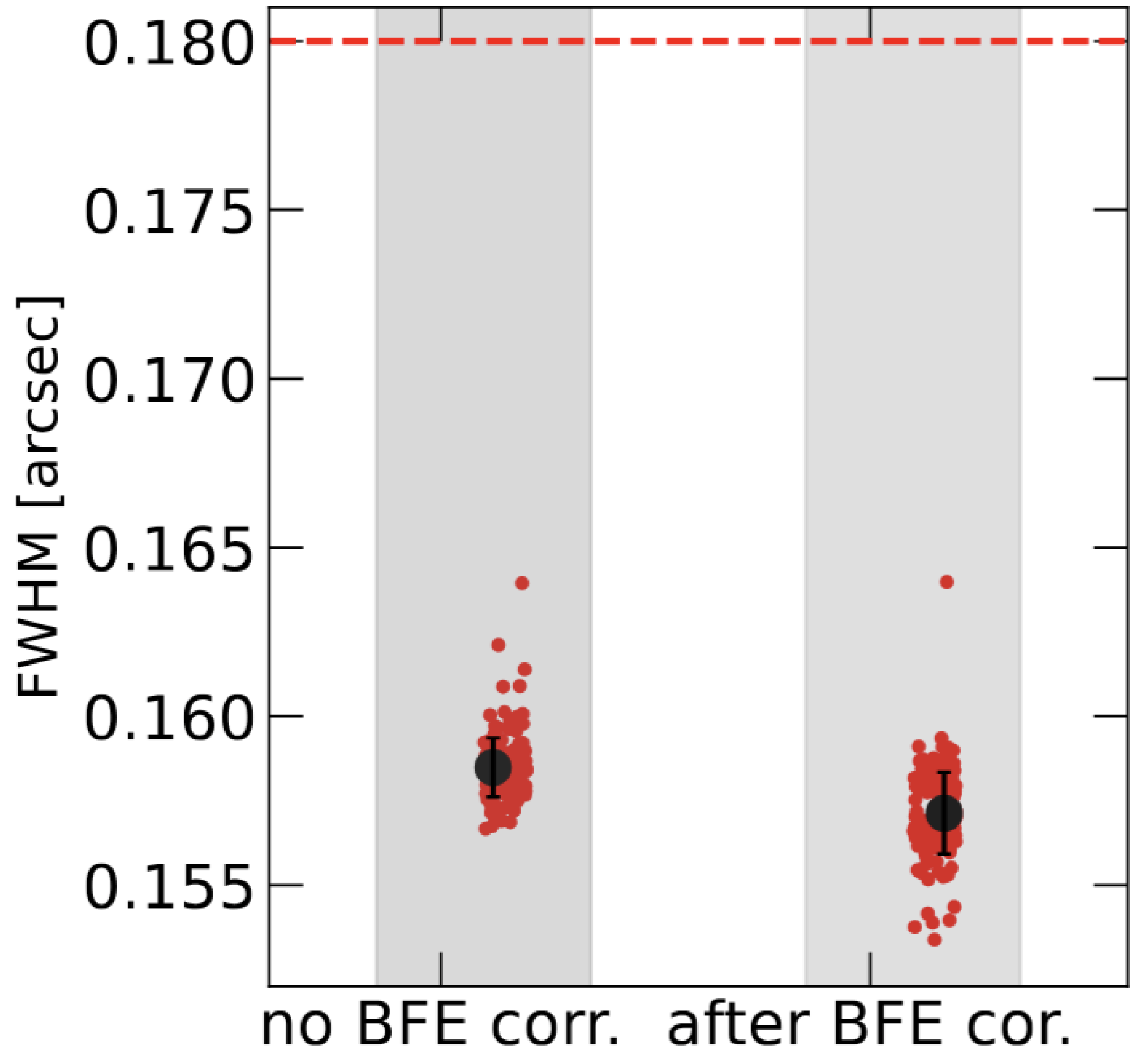
CONSEQUENCE:
Star PSF broaden with increasing flux!

PROBLEM for WL:
Bright stars are usually used to estimate the PSF, while faint galaxies used for WL are impacted by faint/smaller PSF.
Overcorrecting for the PSF might lead to shear overestimation.



Guyonnet+2015

McCracken+2025

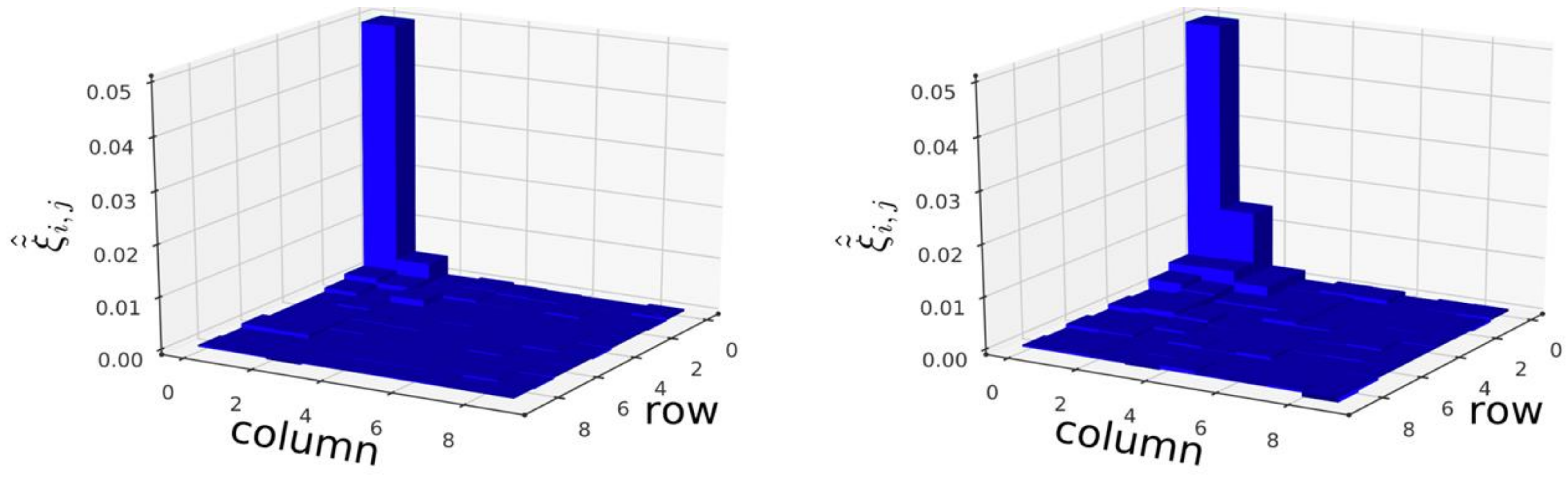


Brighter-Fatter effect: diagnostic and correction

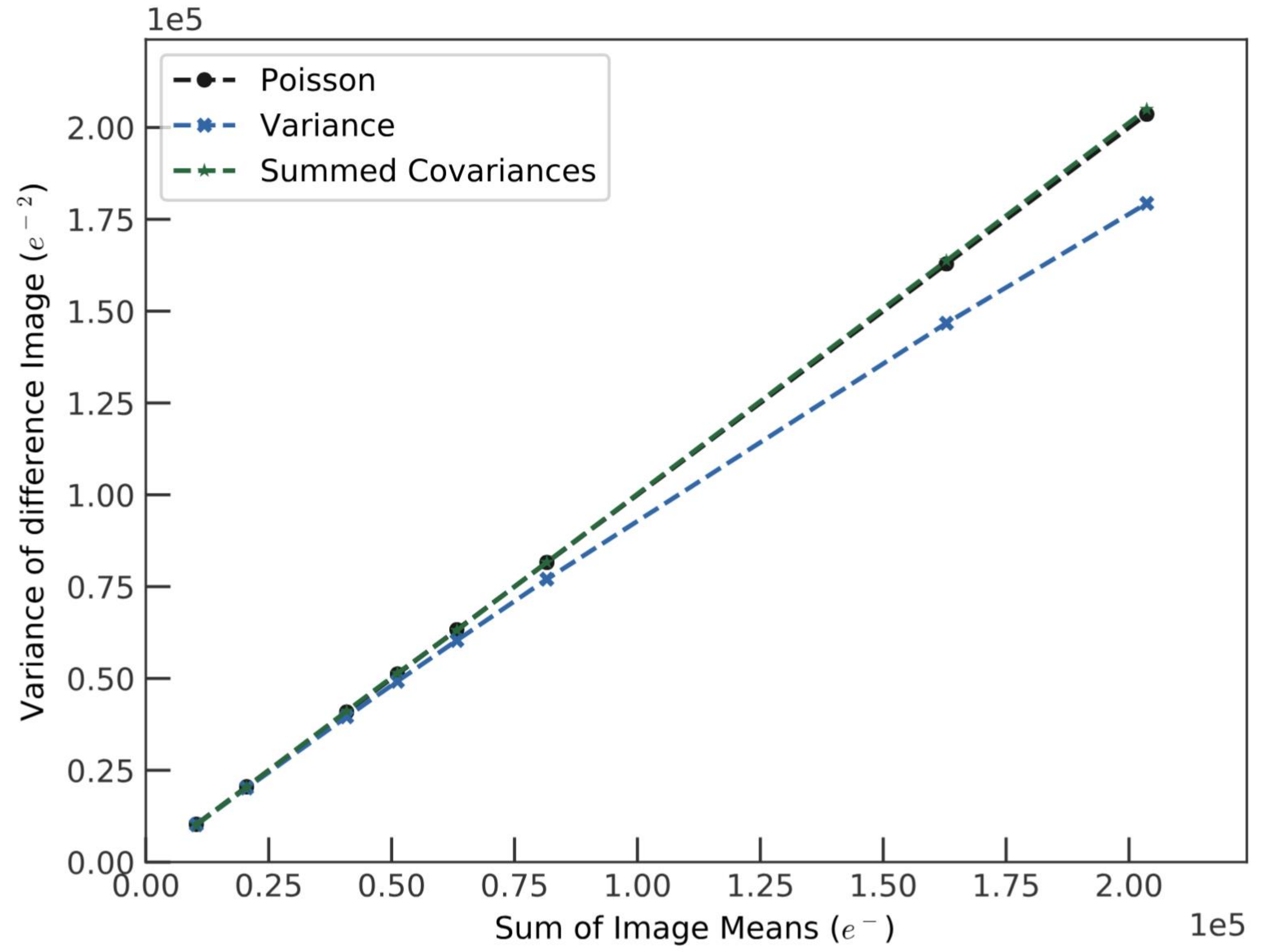
The response of a given pixel to illumination is ~~independent~~ of the content of the neighboring pixels.

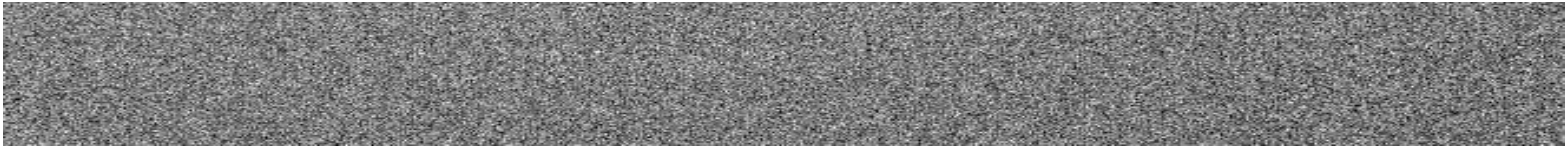
- Neigboring pixels are correlated
- Statistics of pixels is not poissonian anymore

Coulton+2018



(a) Correlations in a 15 second exposure (b) Correlations in a 60 second exposure





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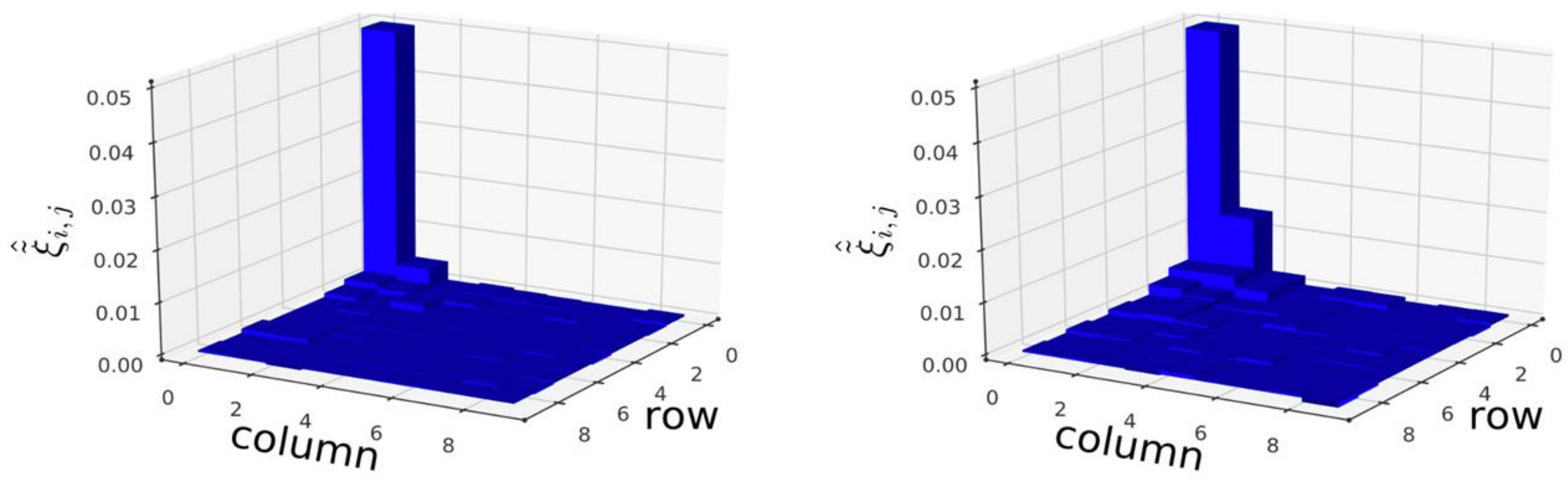
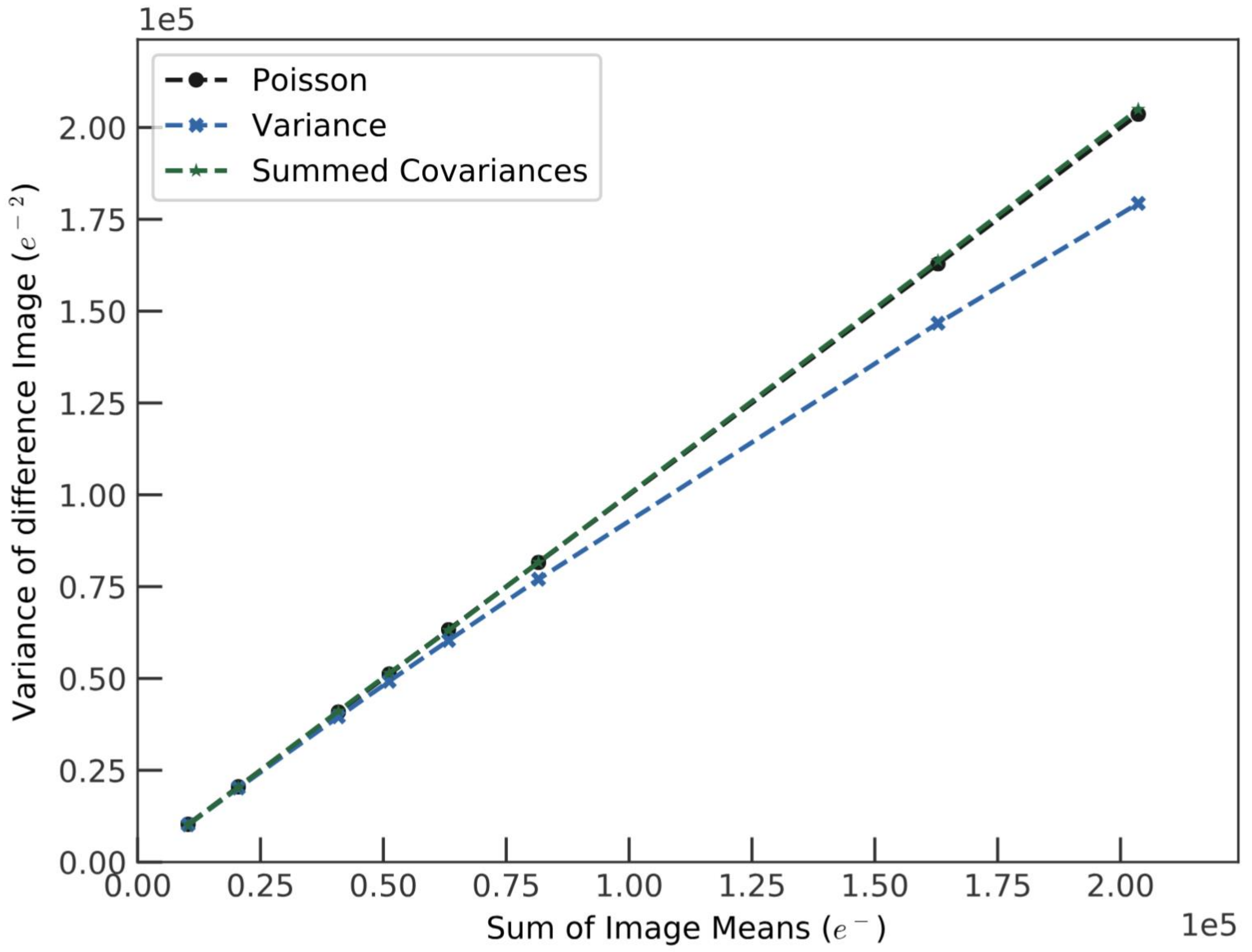


(a) Correlations in a 15 second exposure (b) Correlations in a 60 second exposure



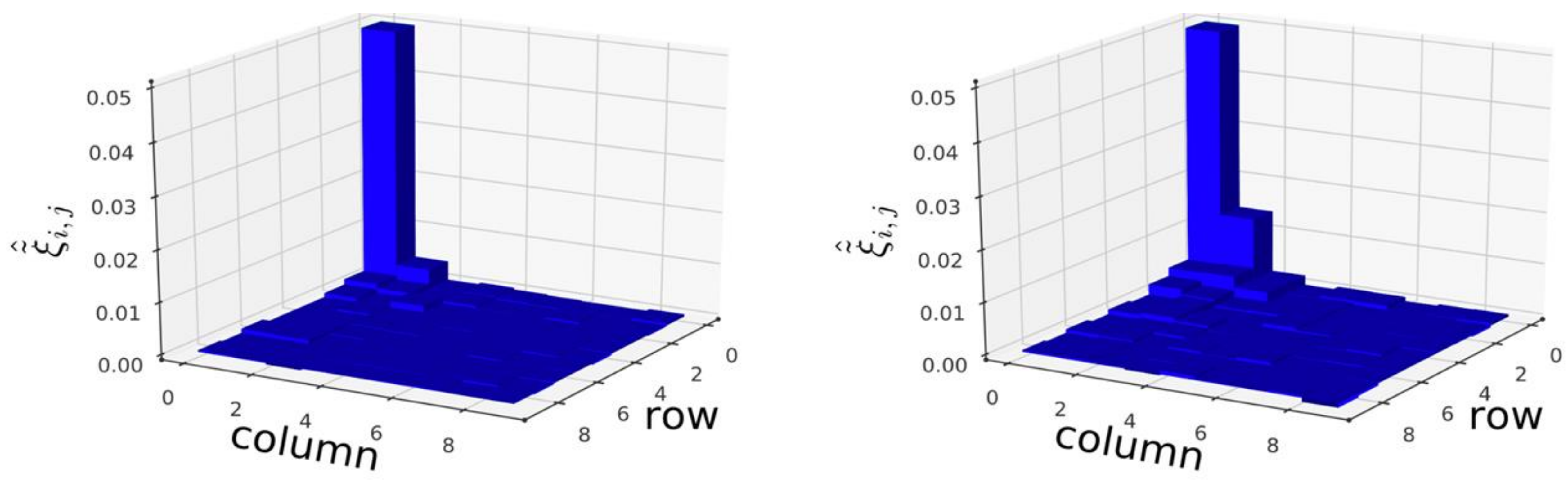
- Correction: The BFE kernel (deflection field) is the solution of the Poisson equation with the pixel covariance as the source term
- The image is convolved with the kernel to compute a deflection potential
- The algorithm calculates the required pixel-to-pixel flux transfers from the gradient of this potential

Brighter-Fatter effect: diagnostic and correction

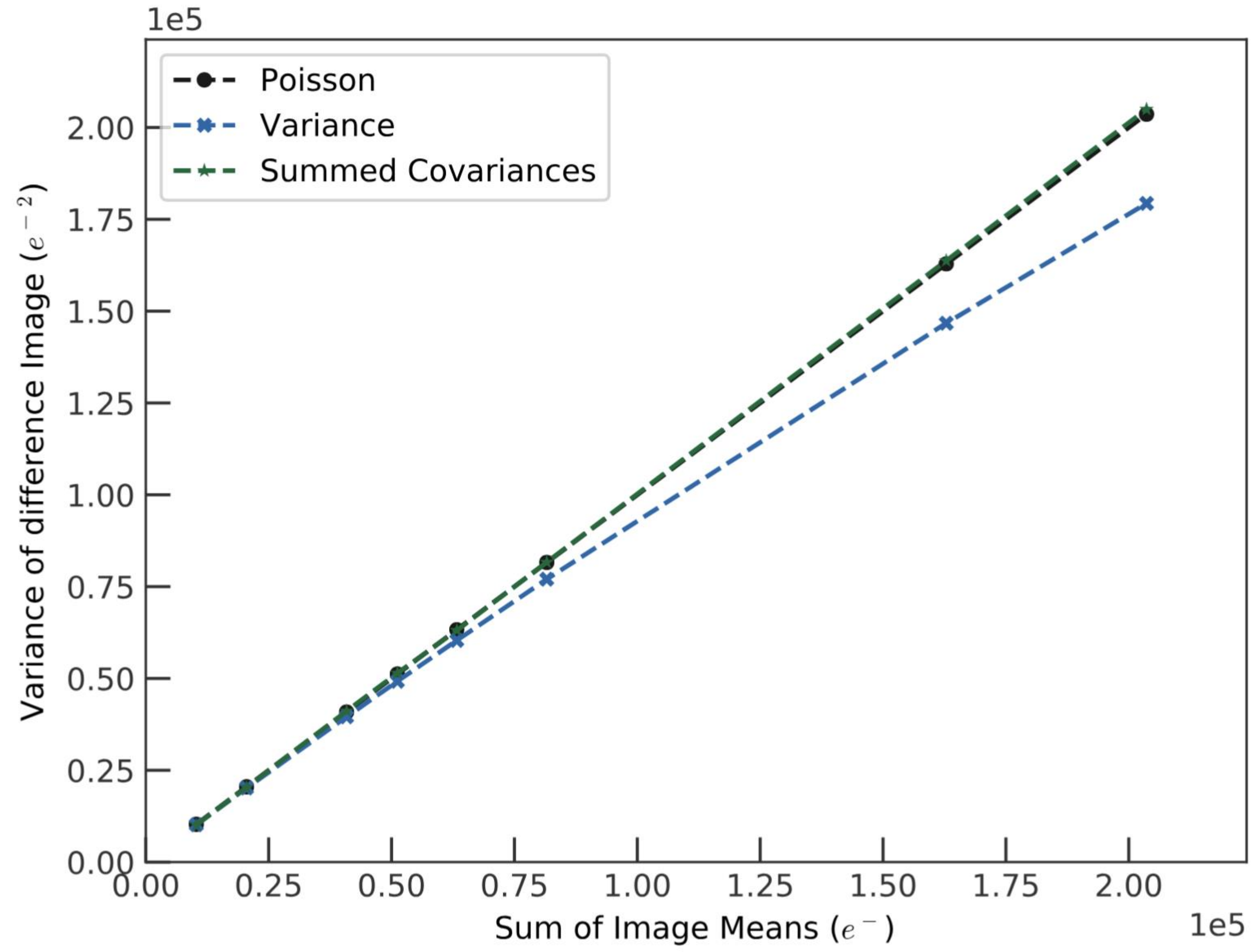
The response of a given pixel to illumination is independent of the content of the neighboring pixels.

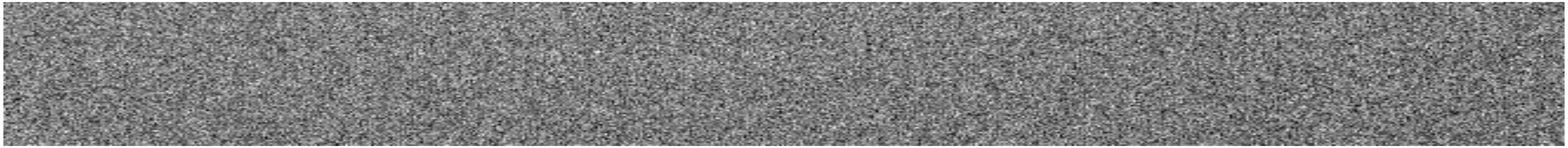
- Neigboring pixels are correlated
- Statistics of pixels is not poissonian anymore

Coulton+2018



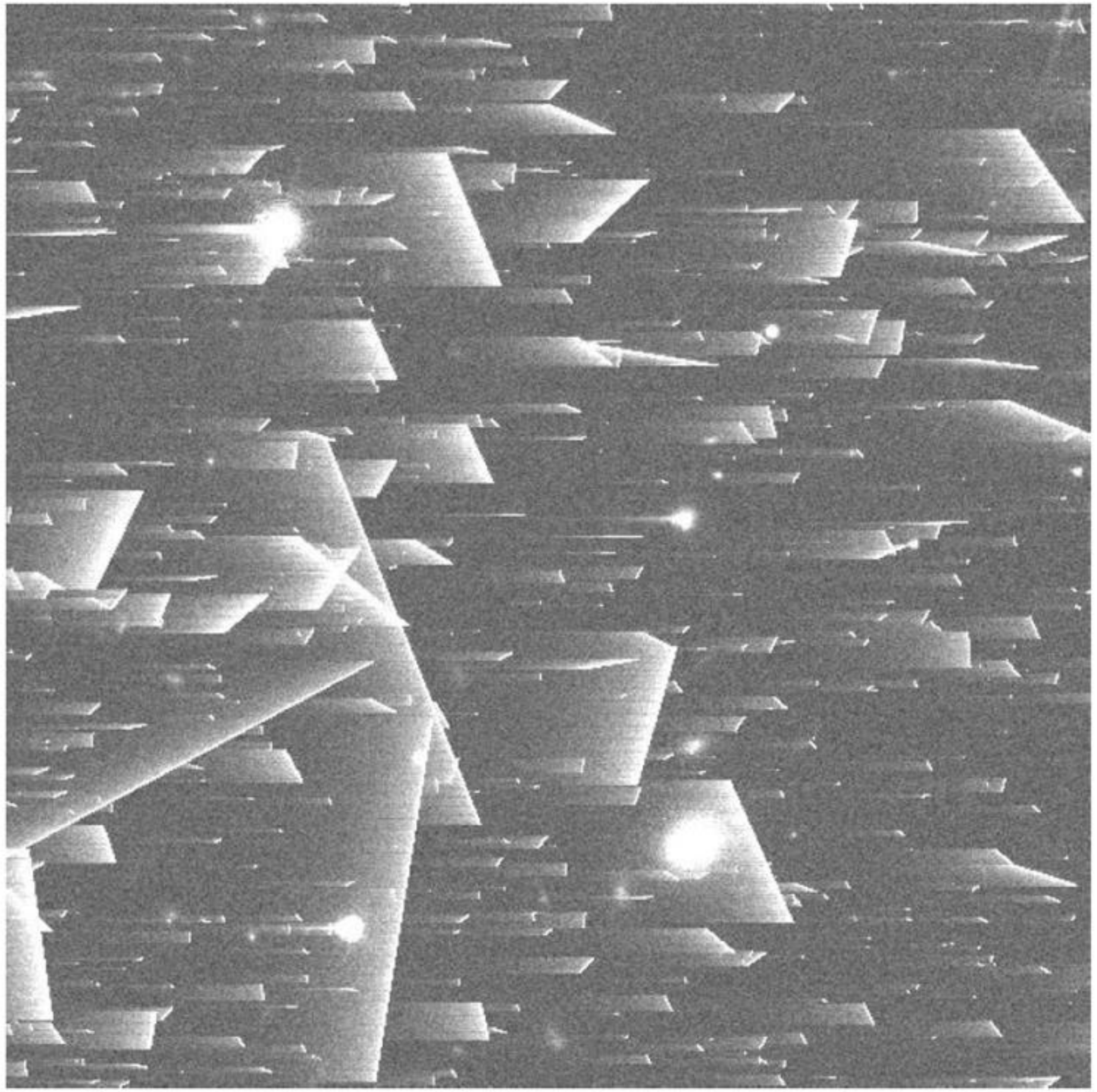
(a) Correlations in a 15 second exposure
(b) Correlations in a 60 second exposure

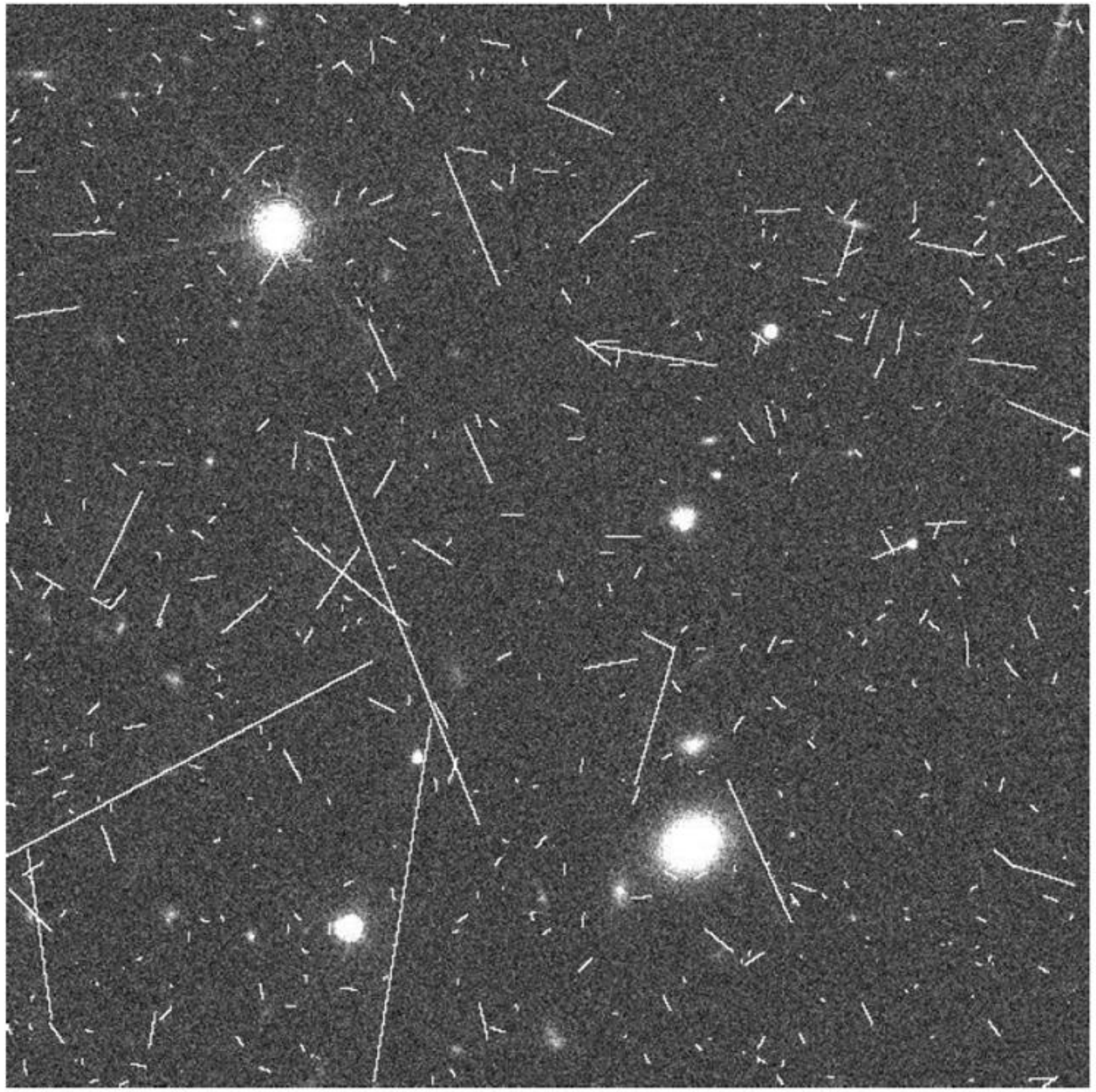




Deterioration due to radiation damage: charge-transfer inefficiency

Credit: ESA/Euclid consortium / NASA





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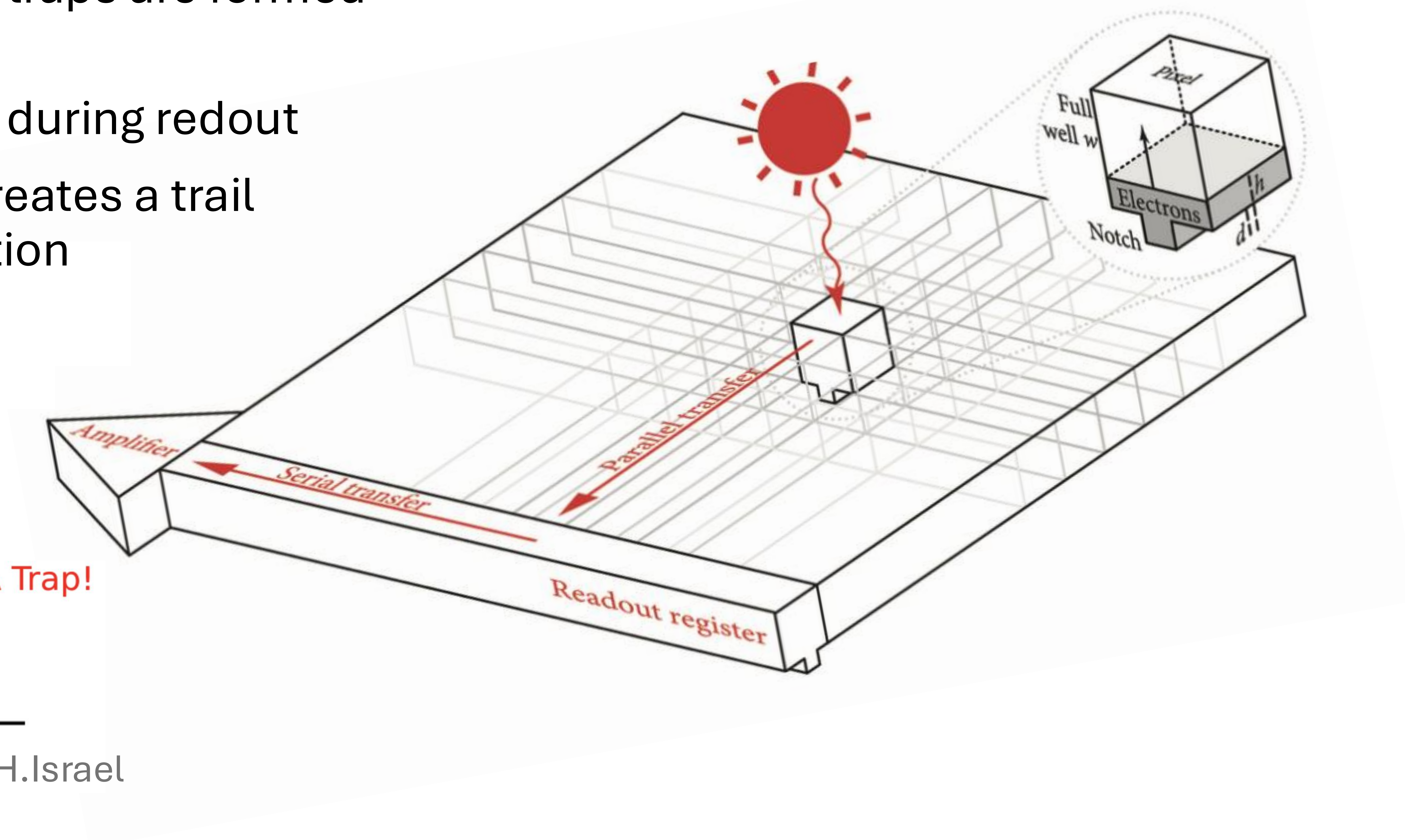
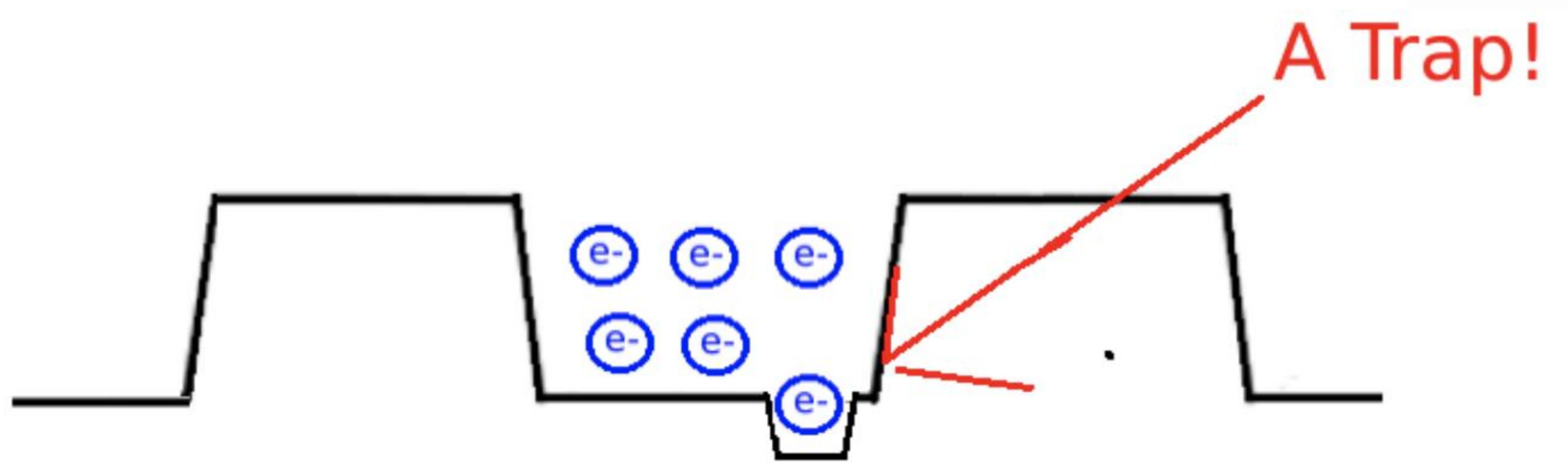
Deterioration due to radiation damage: charge-transfer inefficiency

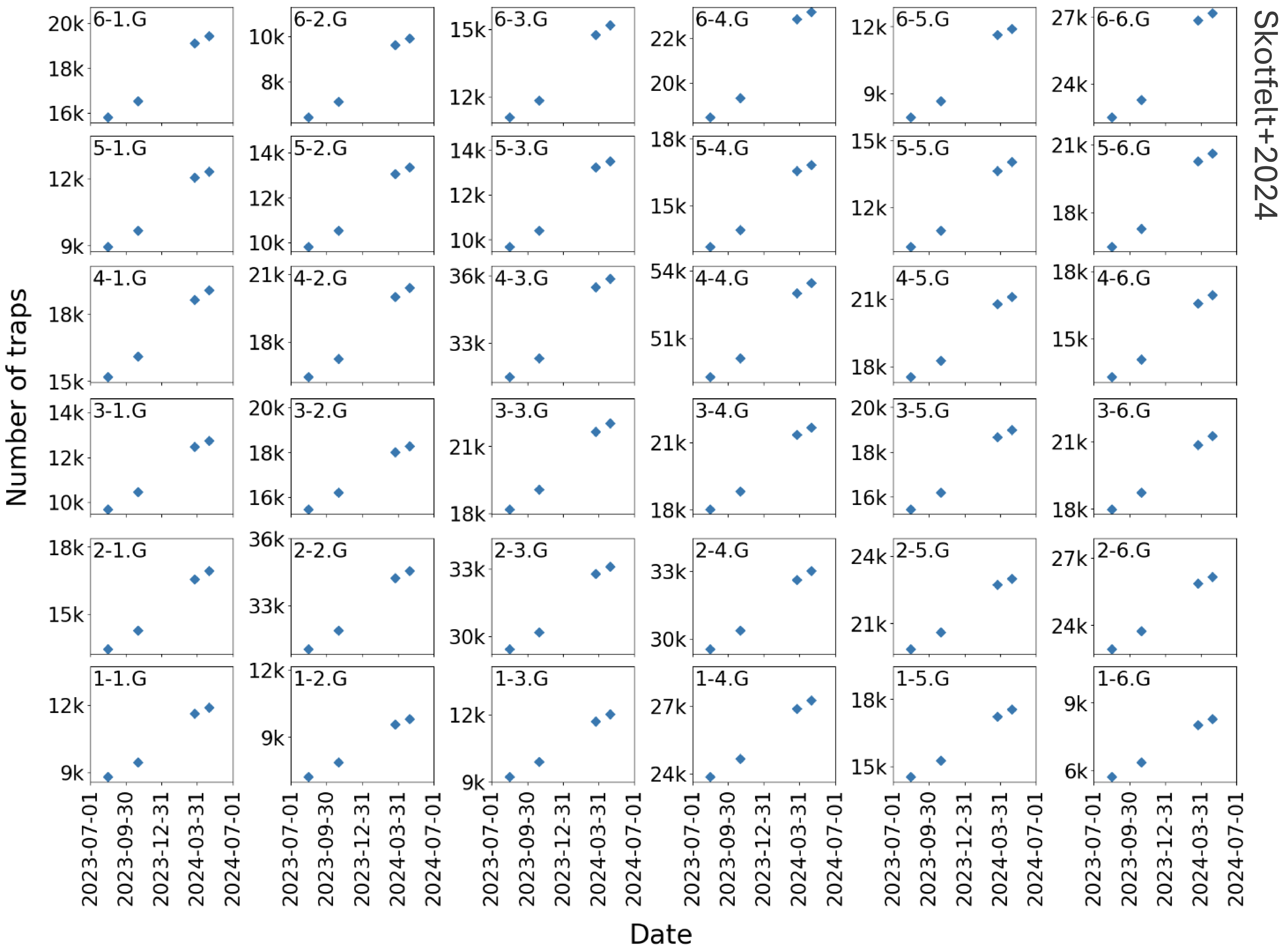
- Due to cosmics, charge traps are formed in the CCD
- Traps capture electrons during redout
- When it is released, it creates a trail along the readout direction





Credit: J. Nightingale, R. Massey, H.Israel

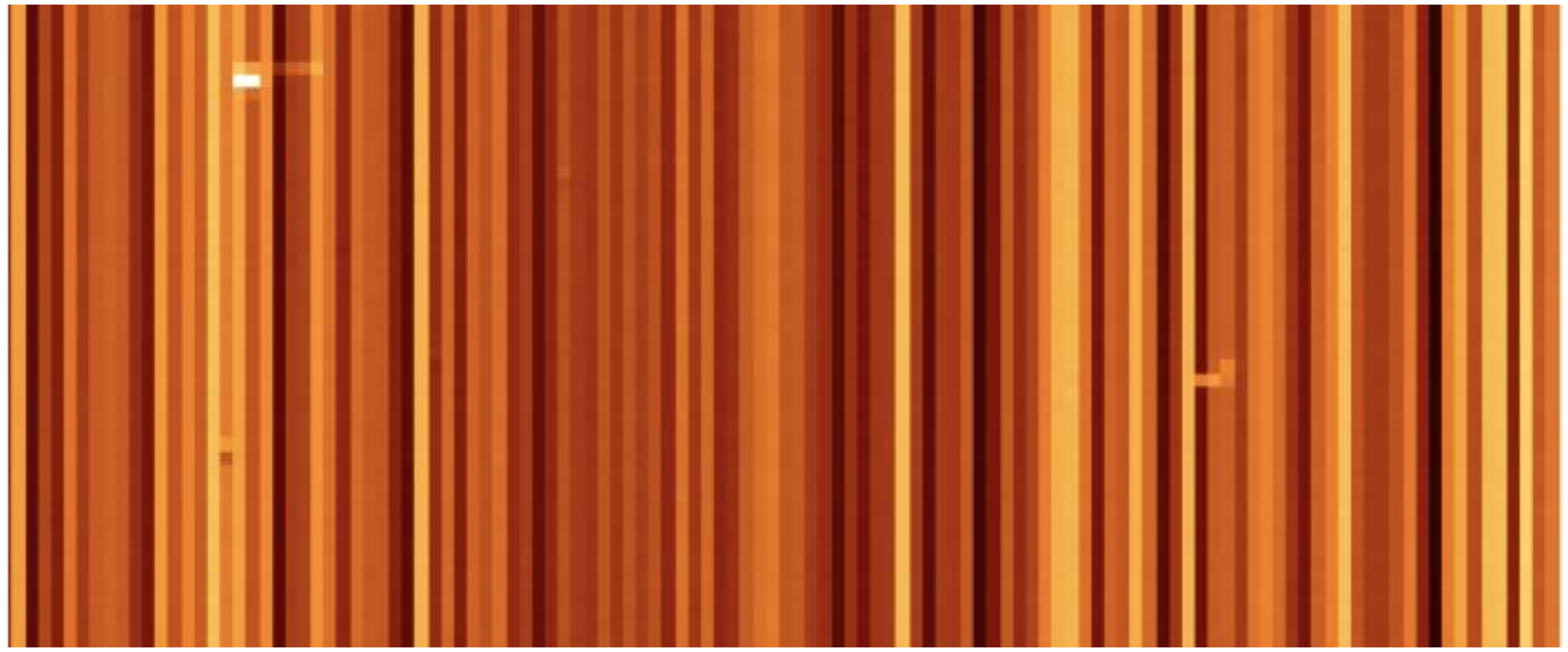
Deterioration due to radiation damage: evolution in Euclid VIS

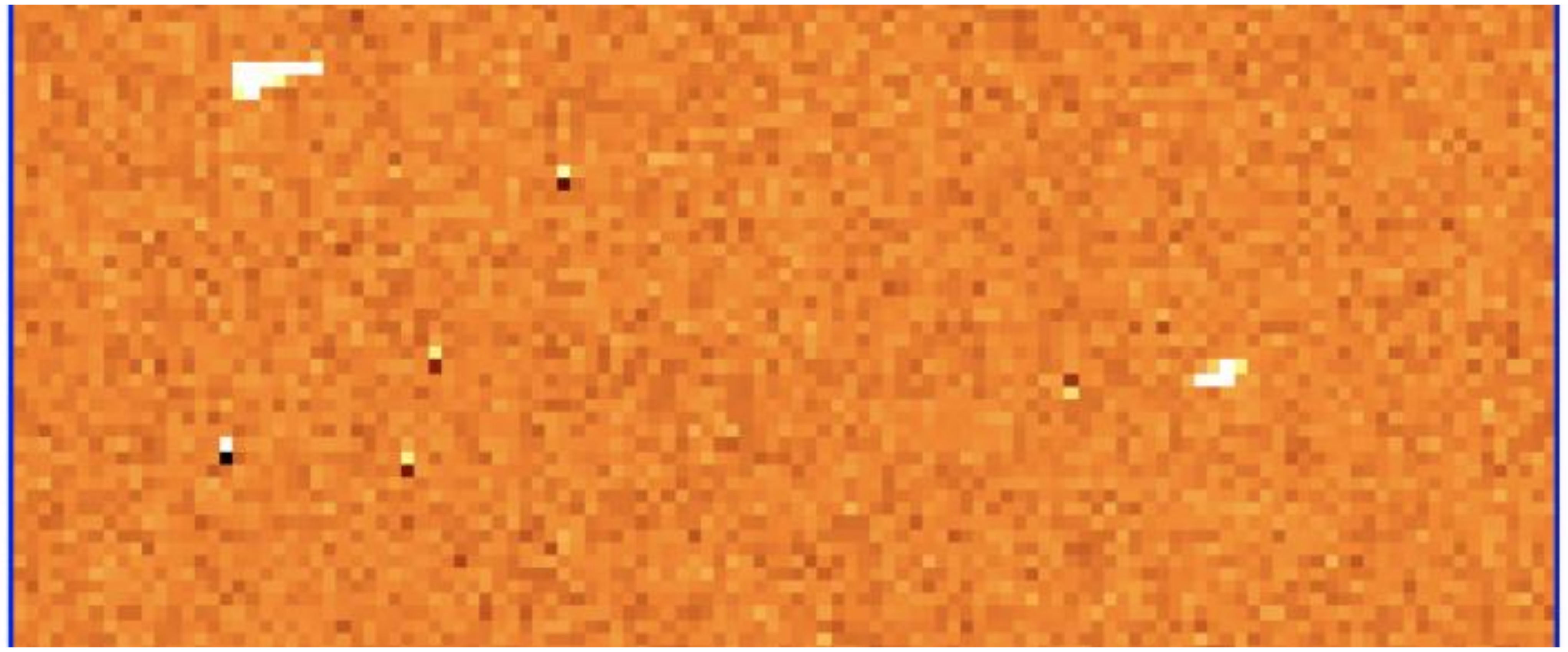


Charge-transfer inefficiency calibration

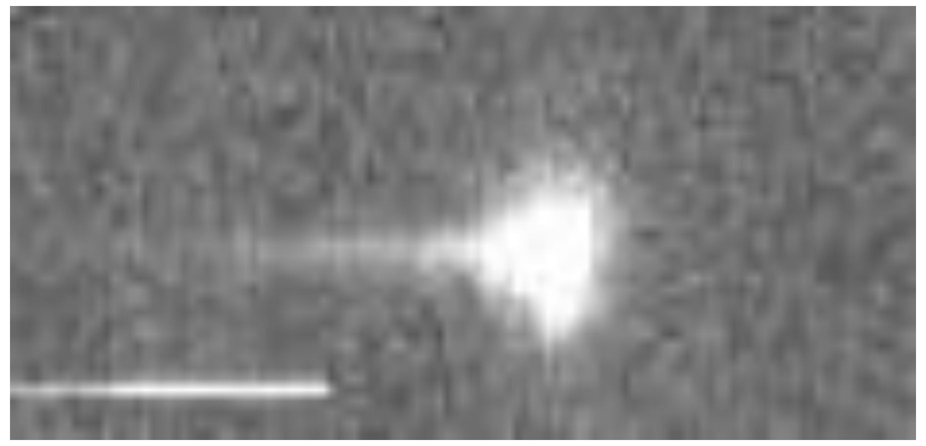
2 daily calibration data sets to identify traps
Charge Injection (trailing of known patterns of charge), Trap Pumping (shuffling charge over defects)

Skottfelt+2024: **Tracking radiation damage of Euclid VIS detectors after 1 year in space**

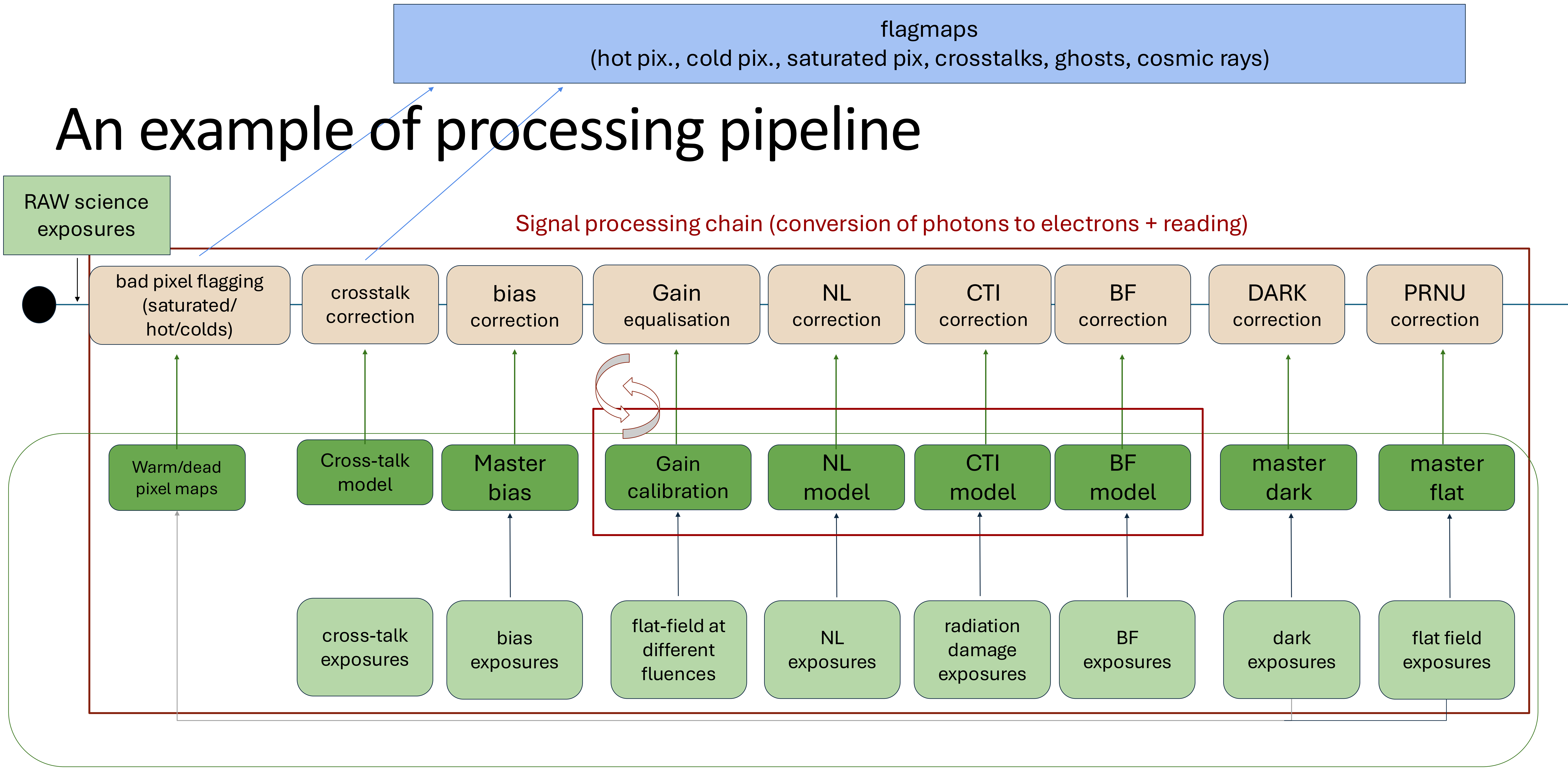




- Model describe the capture & release of electrons. Well understood from solid state physics / lab.
- Parameters describing trap properties on each CCD:
  - Exponential release time constant of each trap.
  - Density ρt of each trap species.
  - The volume fill parameter β.

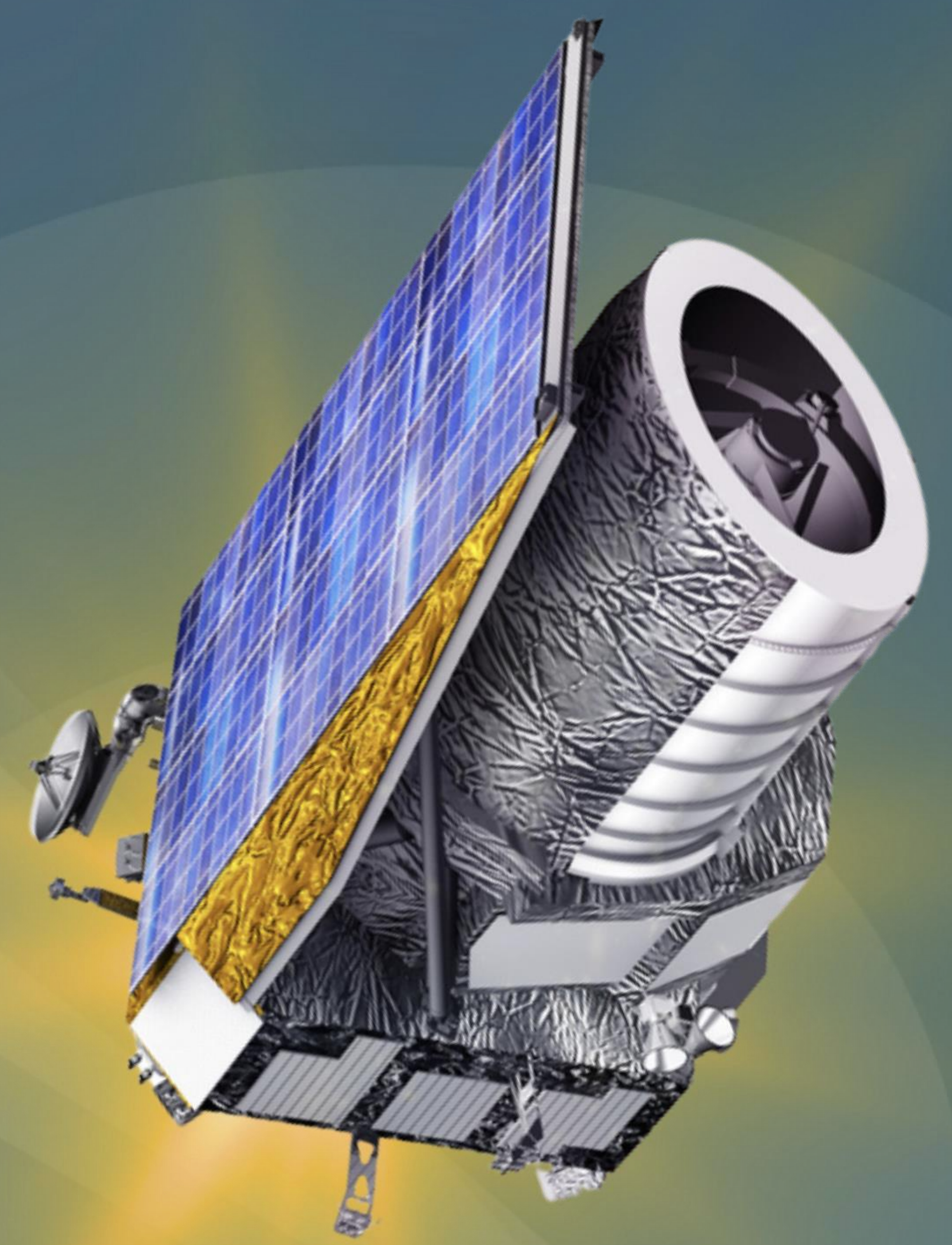


An example of processing pipeline

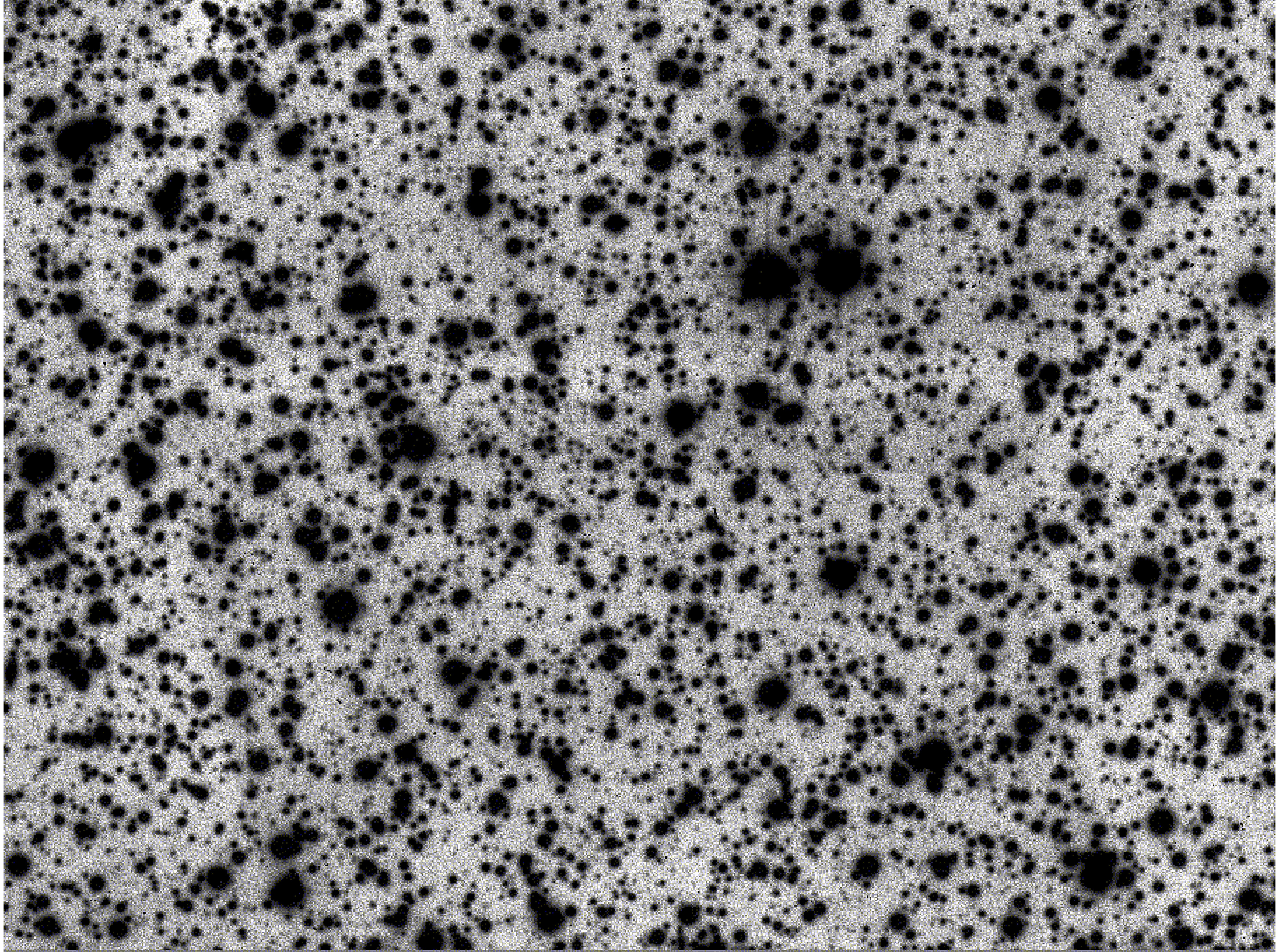



flagmaps
(hot pix., cold pix., saturated pix, crosstalks, ghosts, cosmic rays)
distorsion model / ref astrometry
background & noise maps
PSF model
CR flagging
illumination correction
astrometric calibration
source extraction
background correction
PSF calibration
ghost/ flagging
photometric calibration
calibrated data
stacking
illumination model
distorsion model
scattered light exposure
PSF model
Ghost model
photometric references
self-calibration field exposures
dedicated exposures from PSF calib fields
effects in the optical system

4. Euclid: the adventures of a space telescope



1er Juillet 2023,
Cap Canaveral, Floride



Euclid moving to L2 by CFHT-MegaCam / 12-07-2023

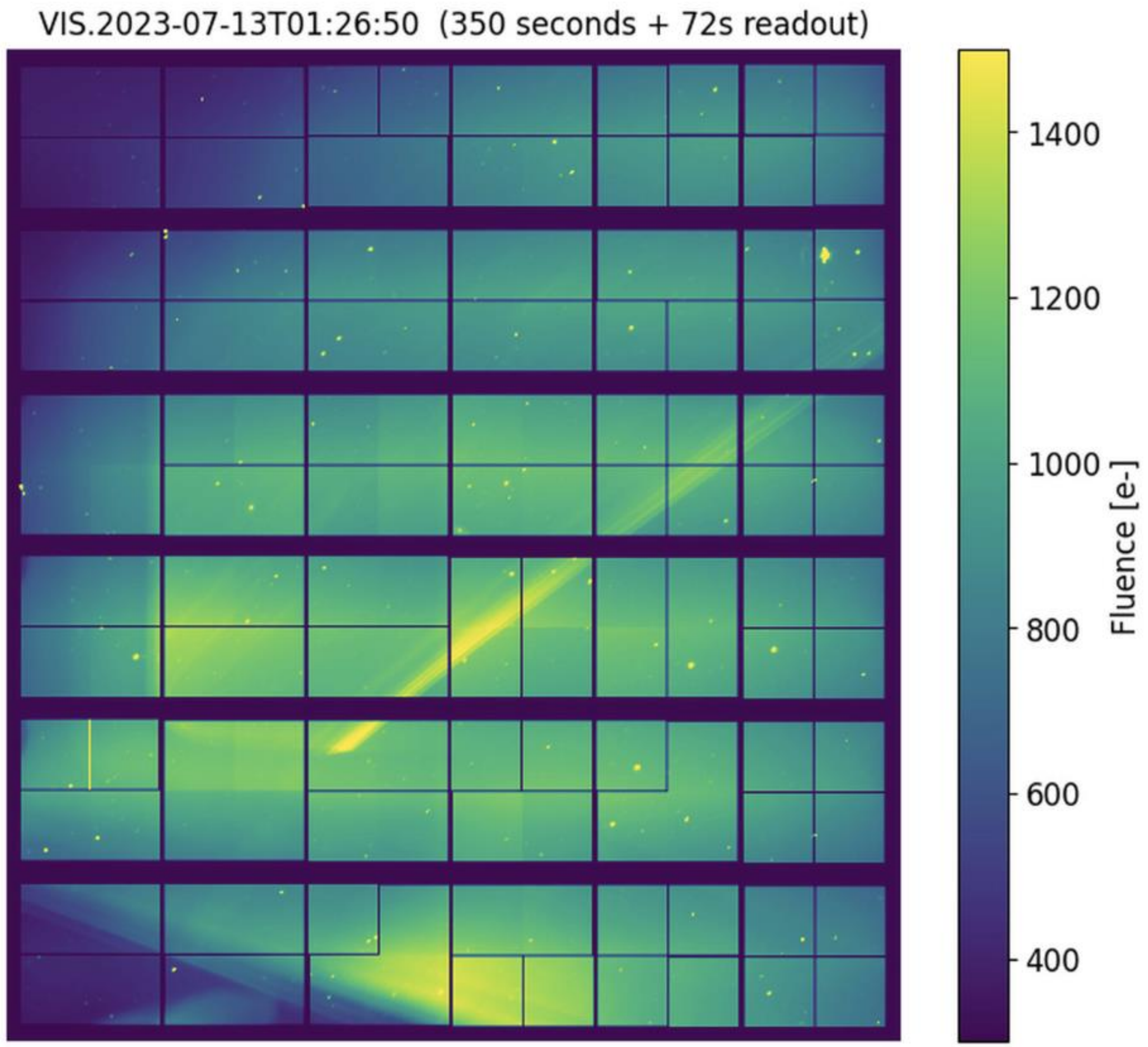
https://www.cosmos.esa.int/documents/10647/11799482/Laureijs_2024_SPIE130920M.pdf

Turning-on VIS

Credit: M. Schirmer

https://www.cosmos.esa.int/documents/10647/11799482/Laureijs_2024_SPIE130920M.pdf

Turning-on VIS

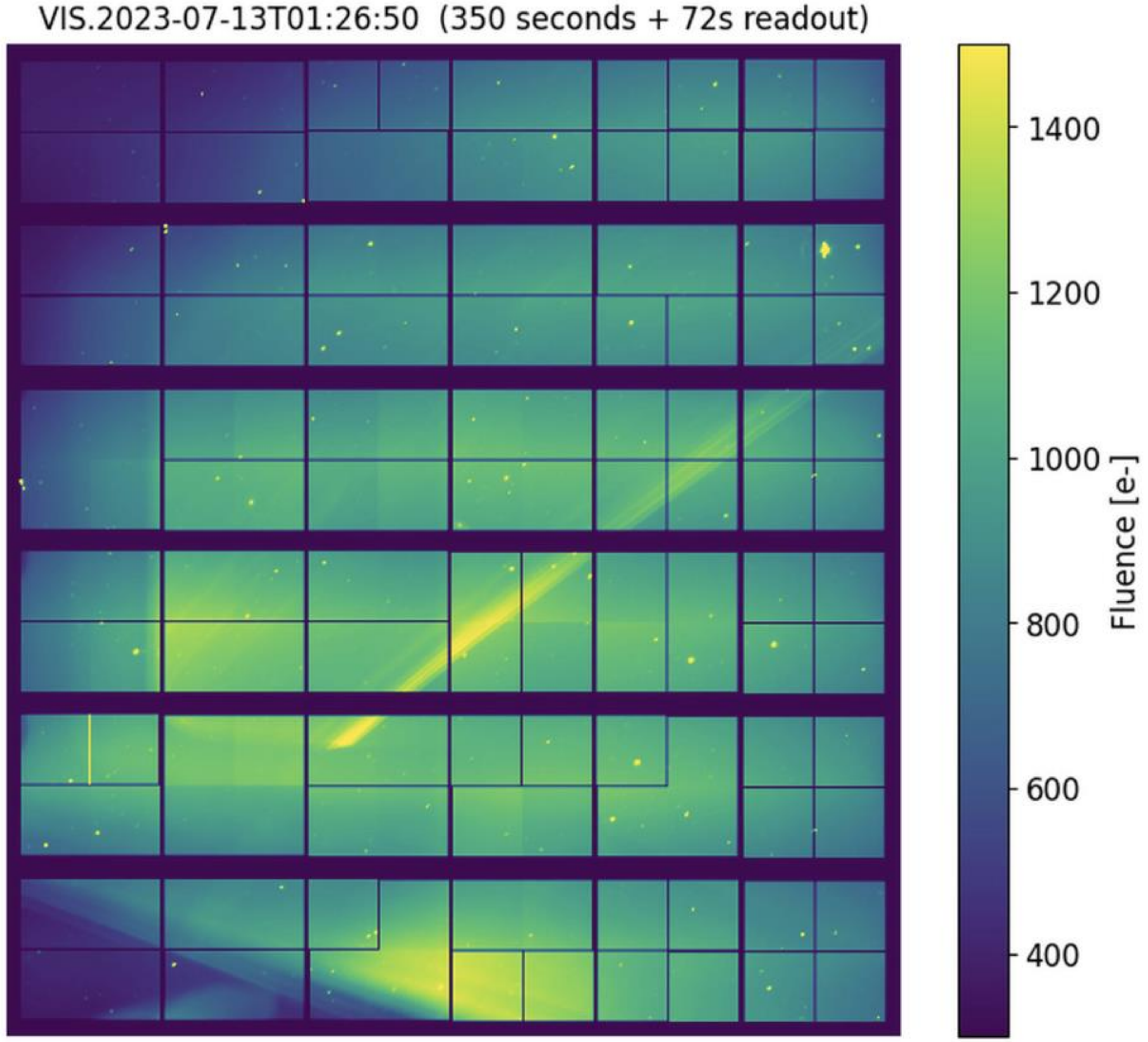


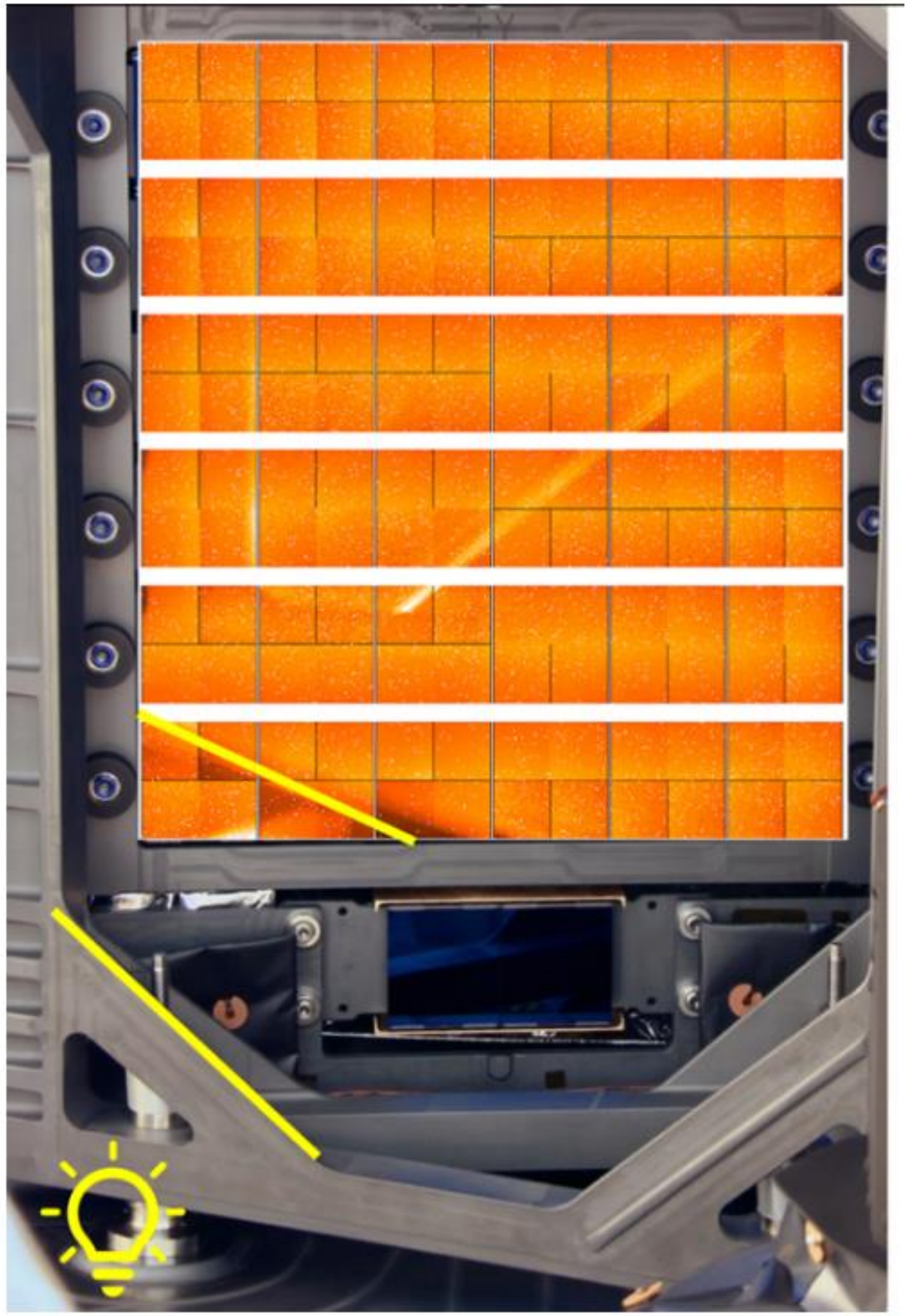
Credit: ESA

Credit: M. Schirmer

https://www.cosmos.esa.int/documents/10647/11799482/Laureijs_2024_SPIE130920M.pdf

Turning-on VIS



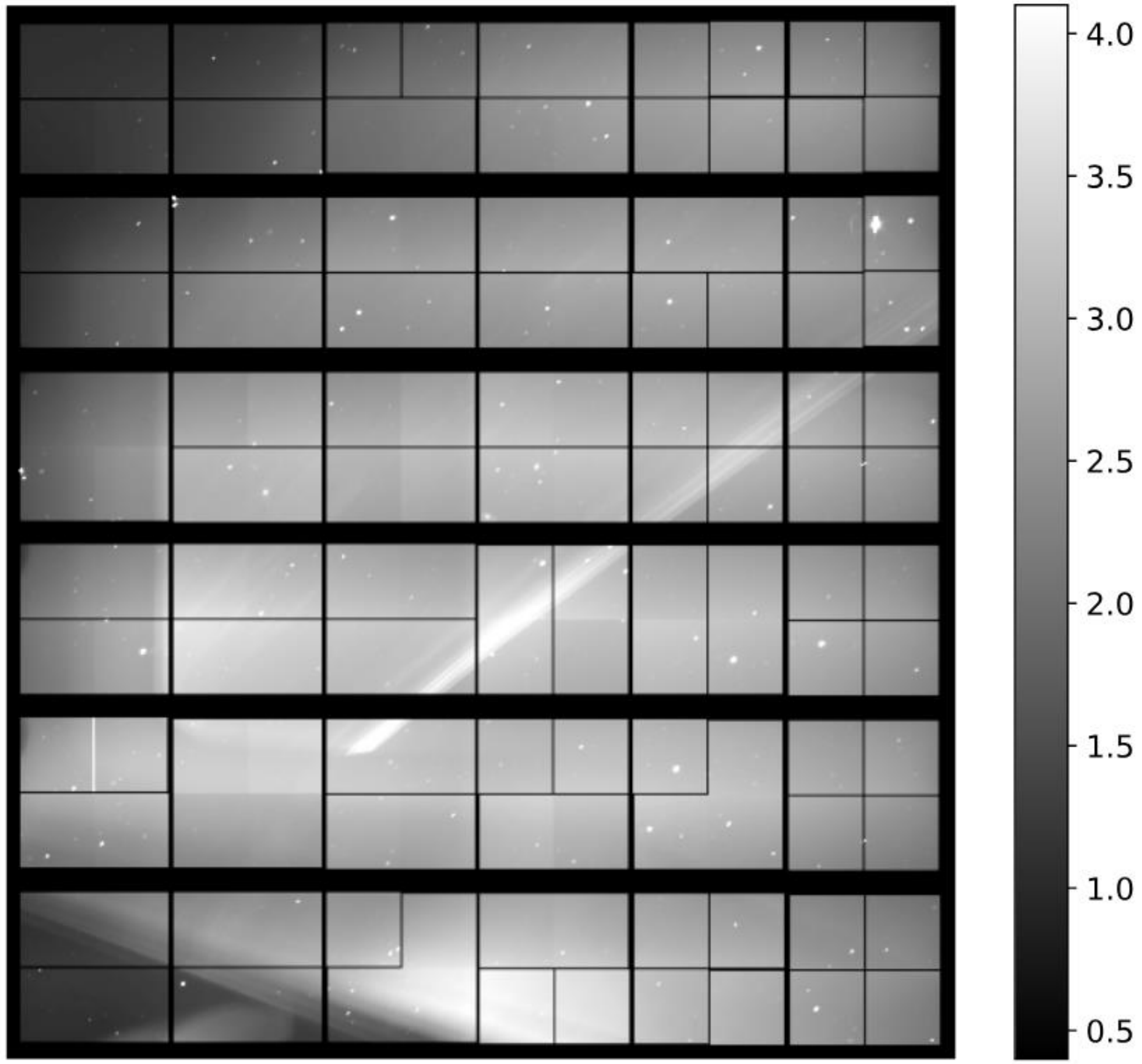


Credit: ESA

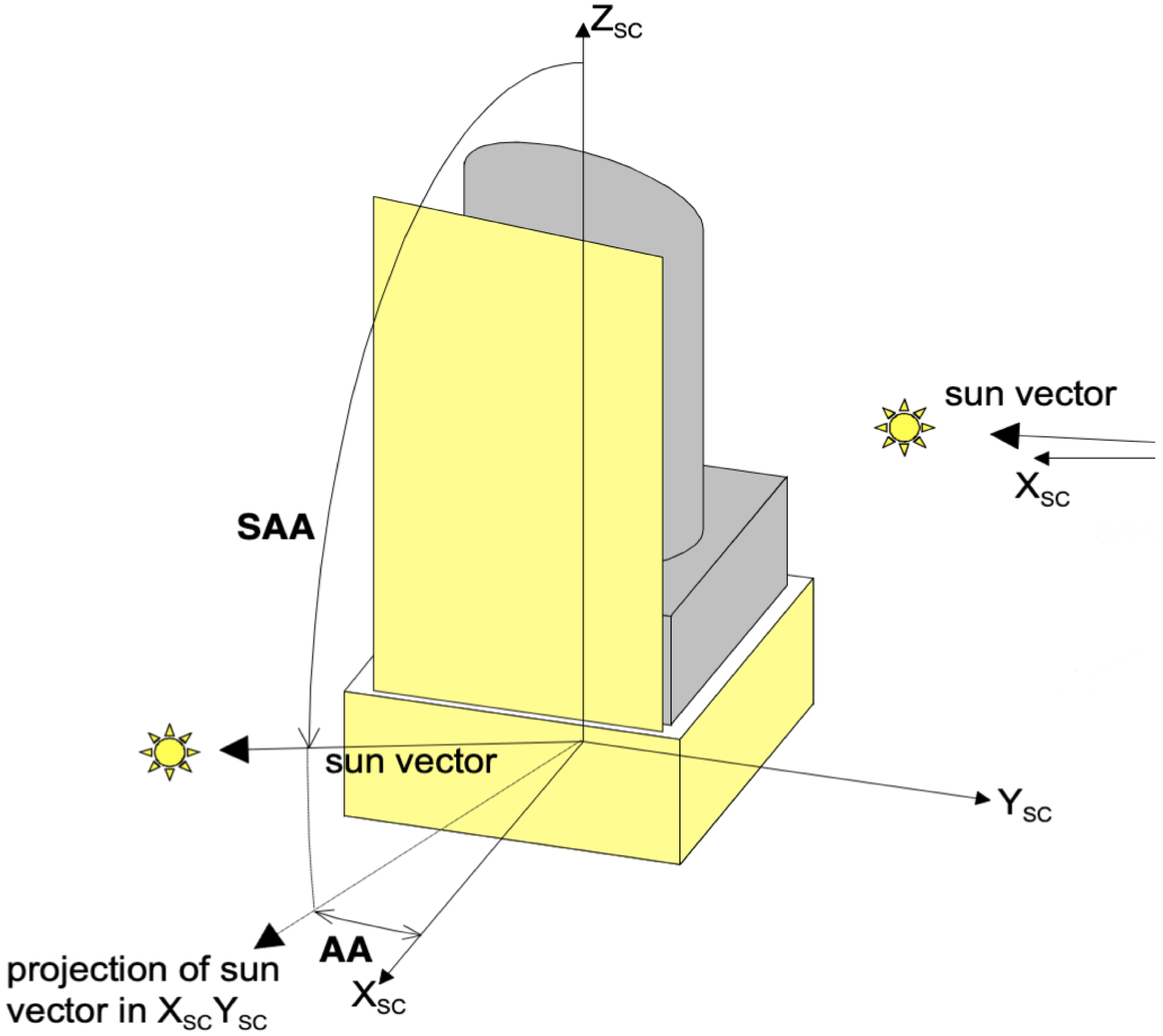
https://www.cosmos.esa.int/documents/10647/11799482/Laureijs_2024_SPIE130920M.pdf

Turning-on VIS

AA = 0



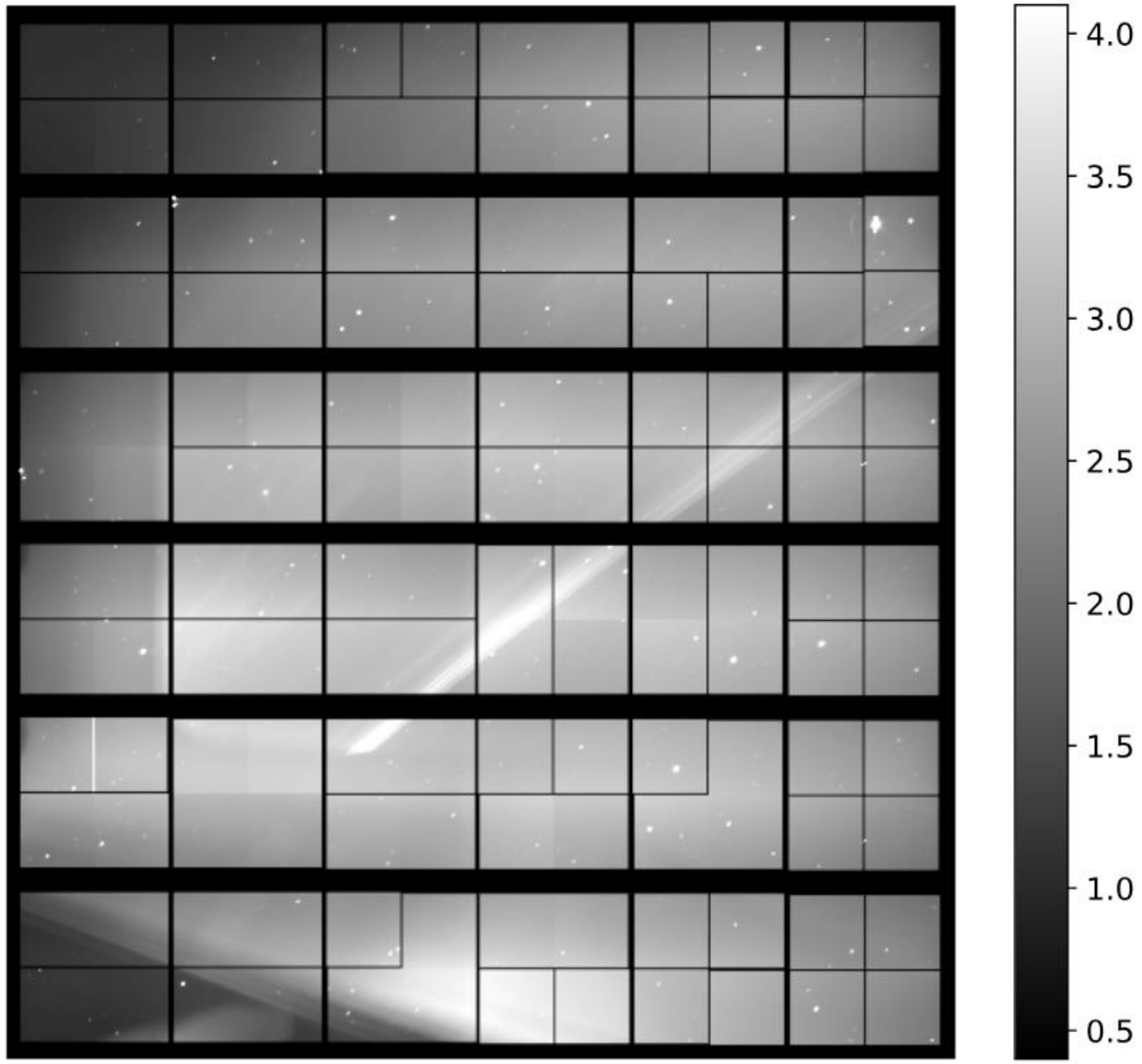
Scaramella+22



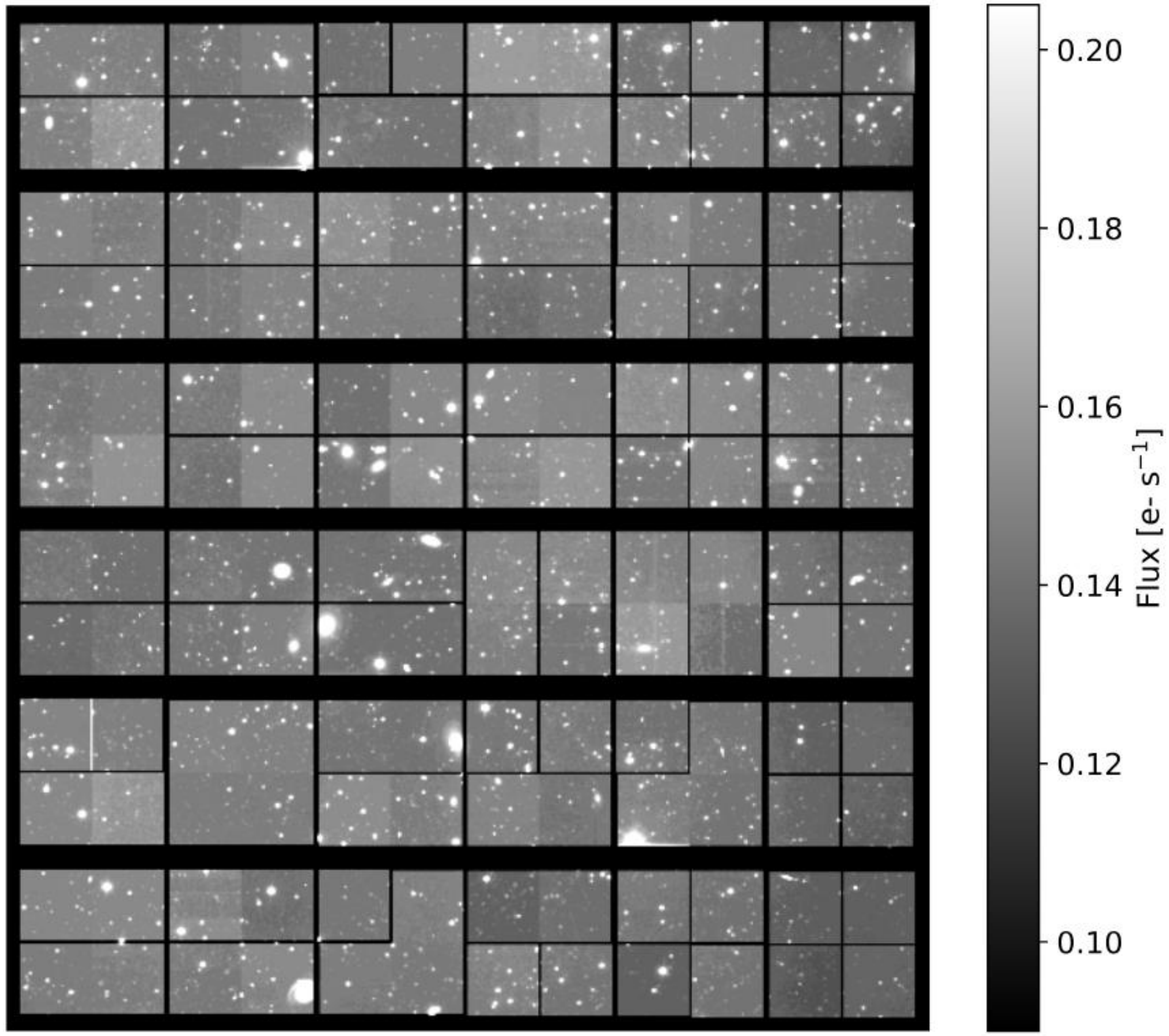
https://www.cosmos.esa.int/documents/10647/11799482/Laureijs_2024_SPIE130920M.pdf

Straylight depends on the telescope attitude with respect to the sun

AA = 0



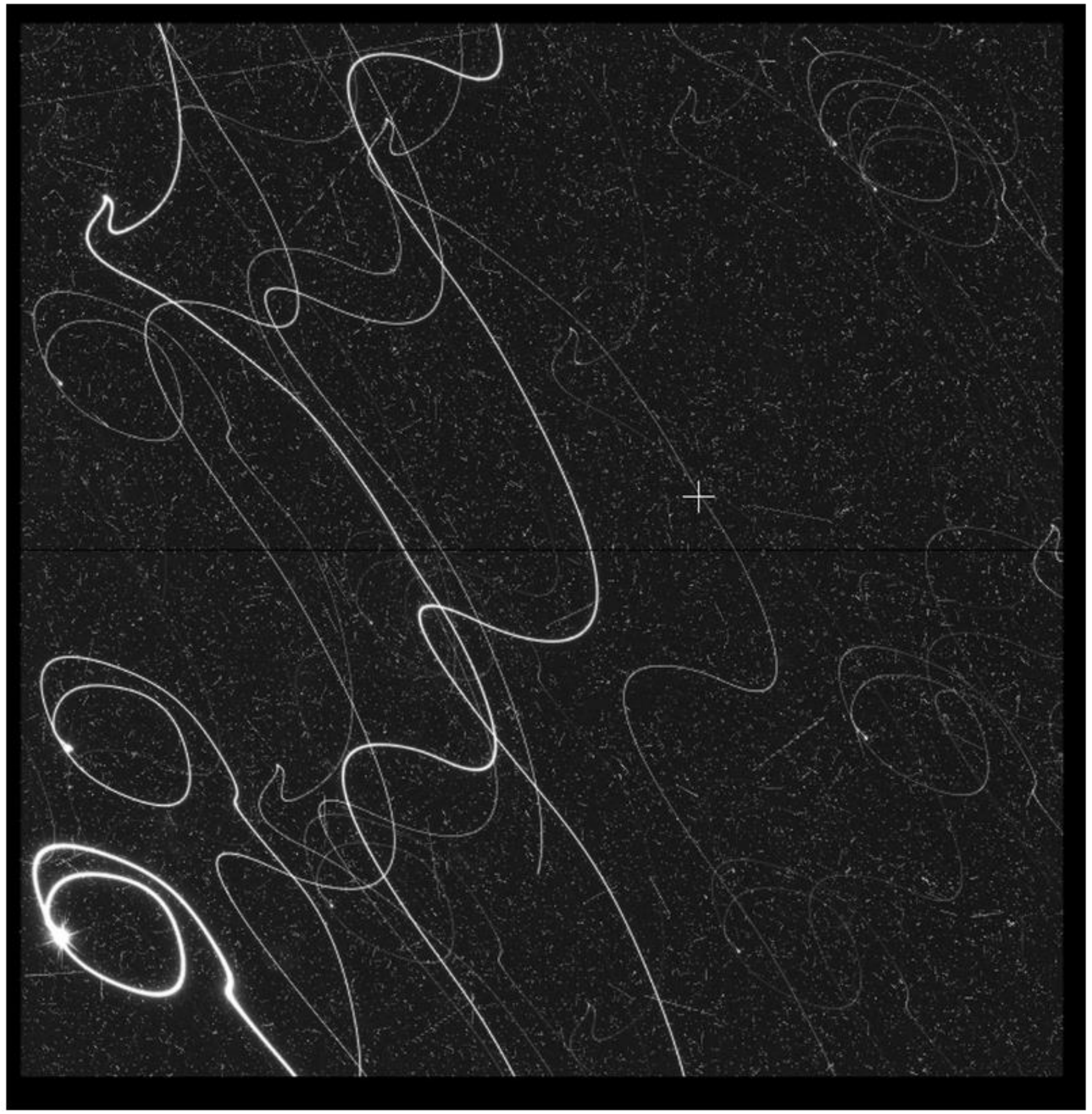
AA = -2.9

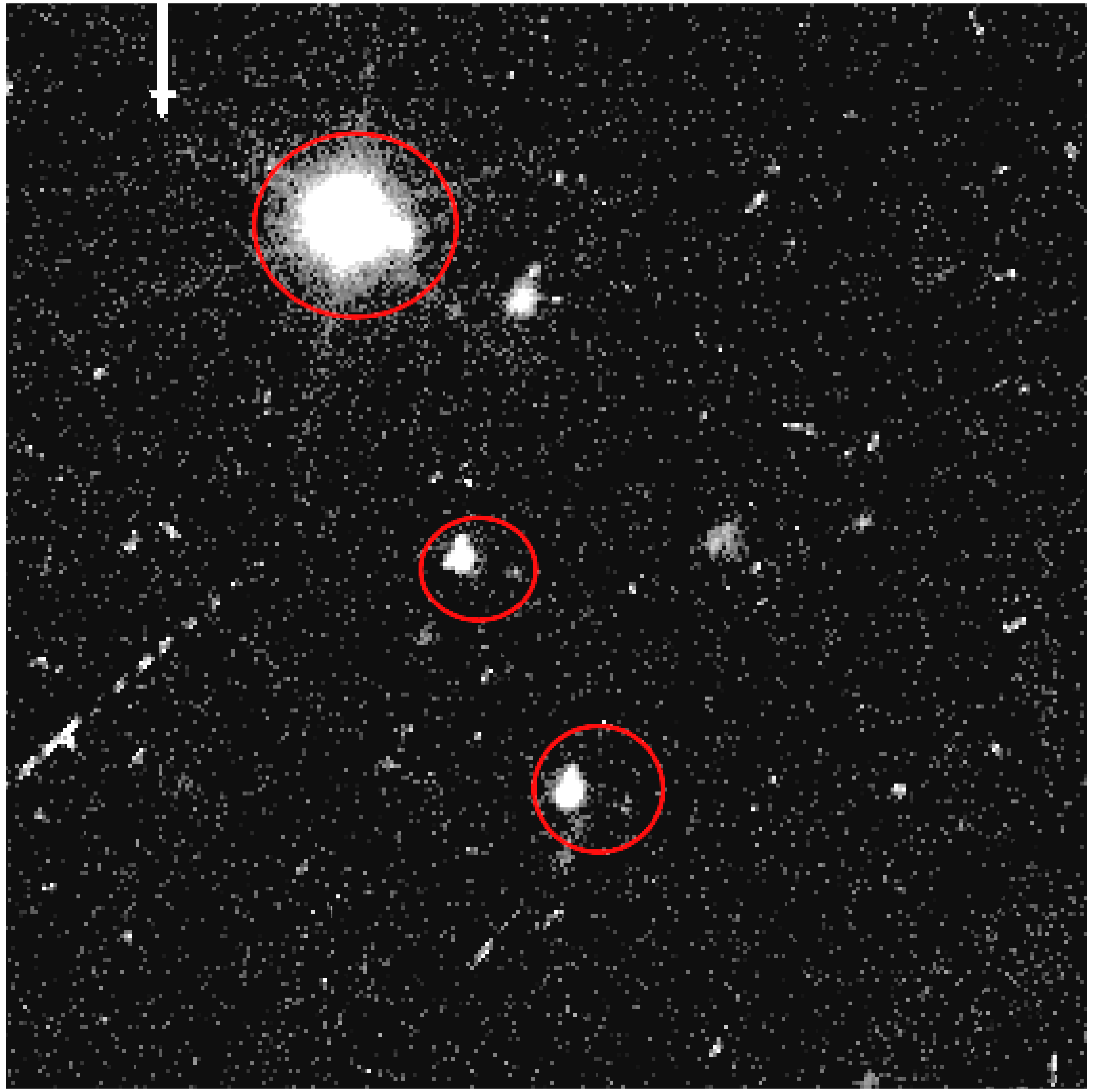


Need to design again the entire survey to account for the new AA constraint: impact on survey area

Fine guidance sensor (FGS) tracking anomaly

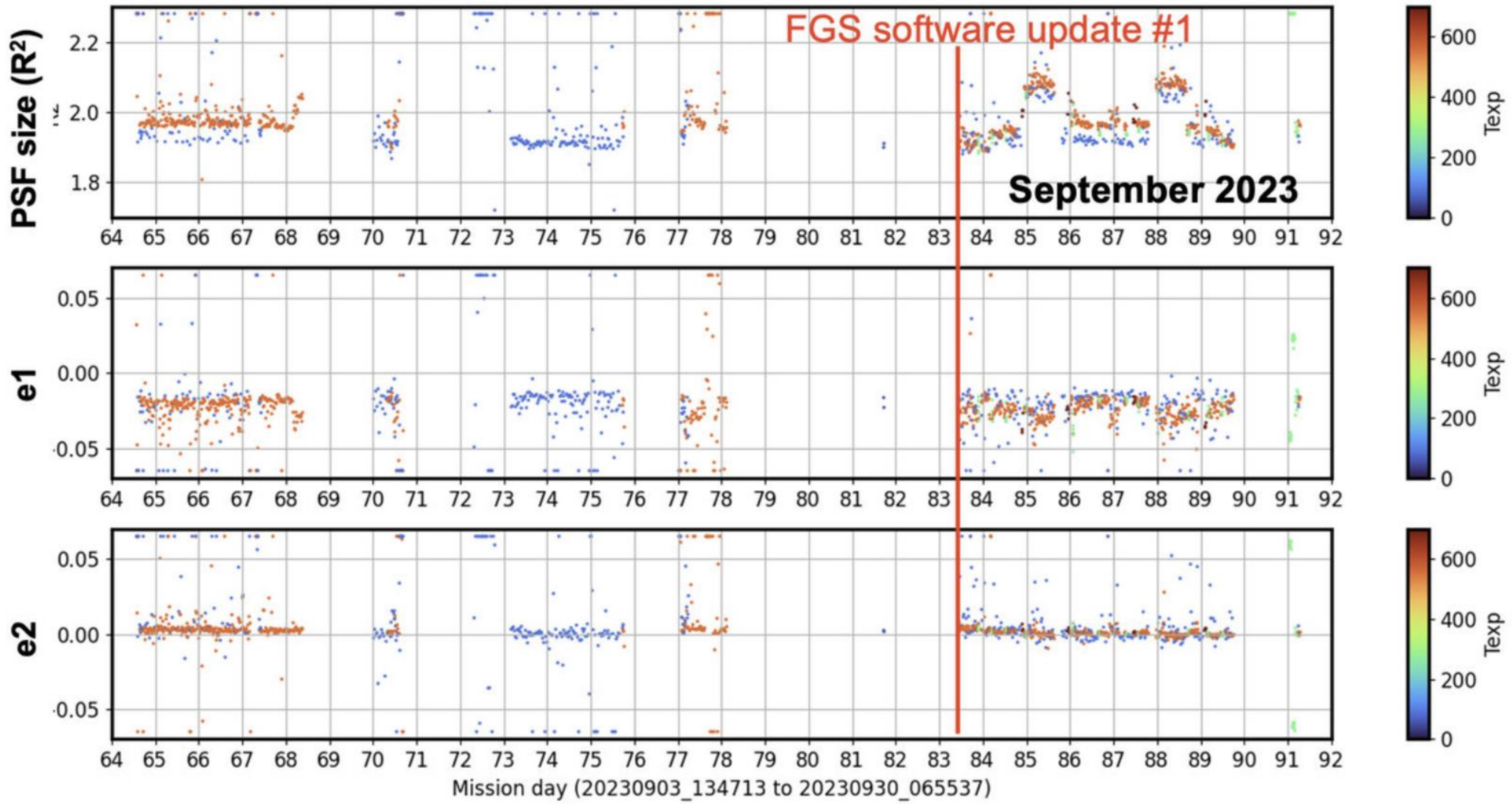
Credit: ESA / Euclid Consortium / TAS-I





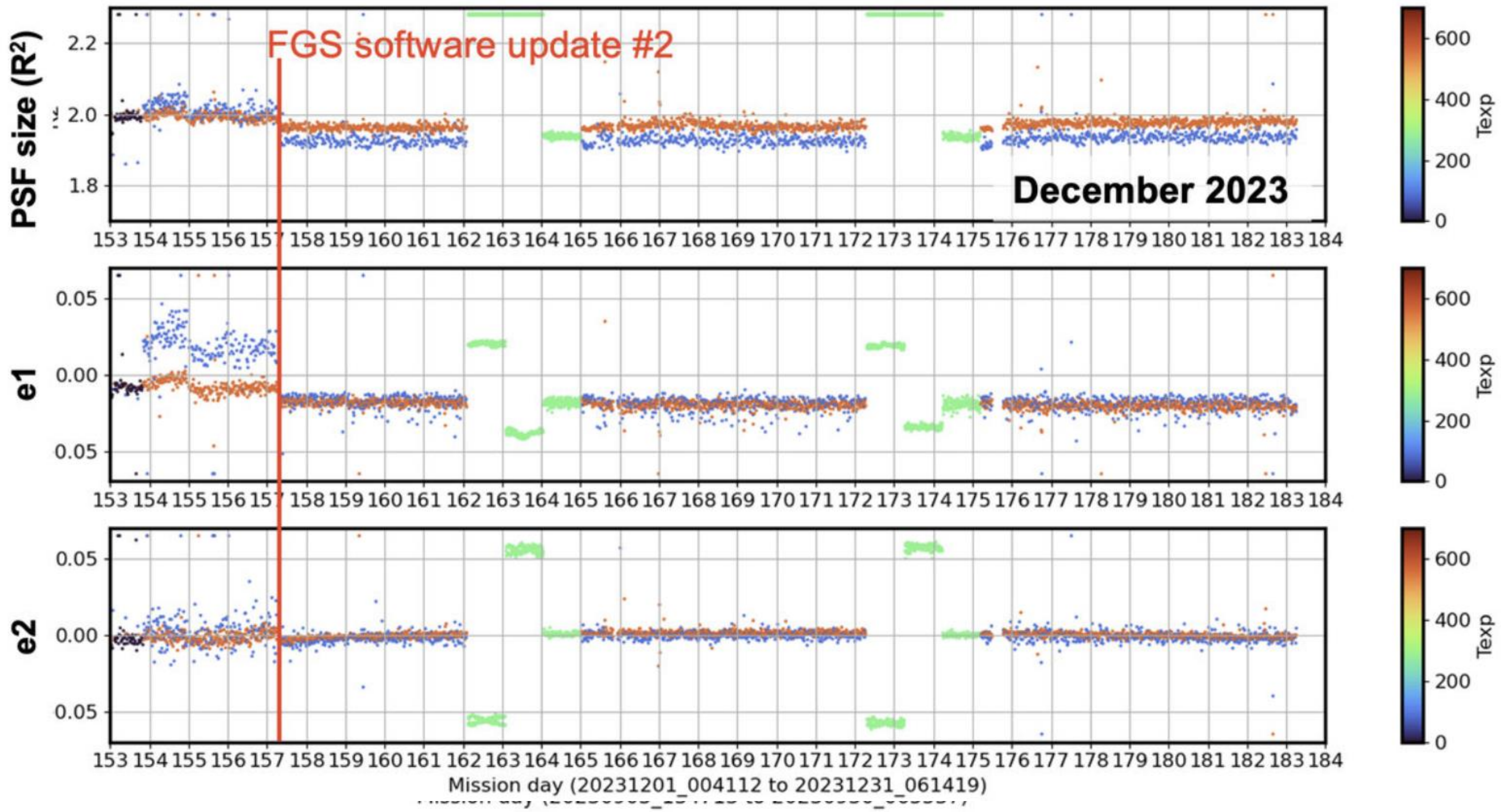
Fine guidance sensor (FGS) tracking anomaly correction

Credit: ESA / Euclid Consortium /NASA / K. Kuijken

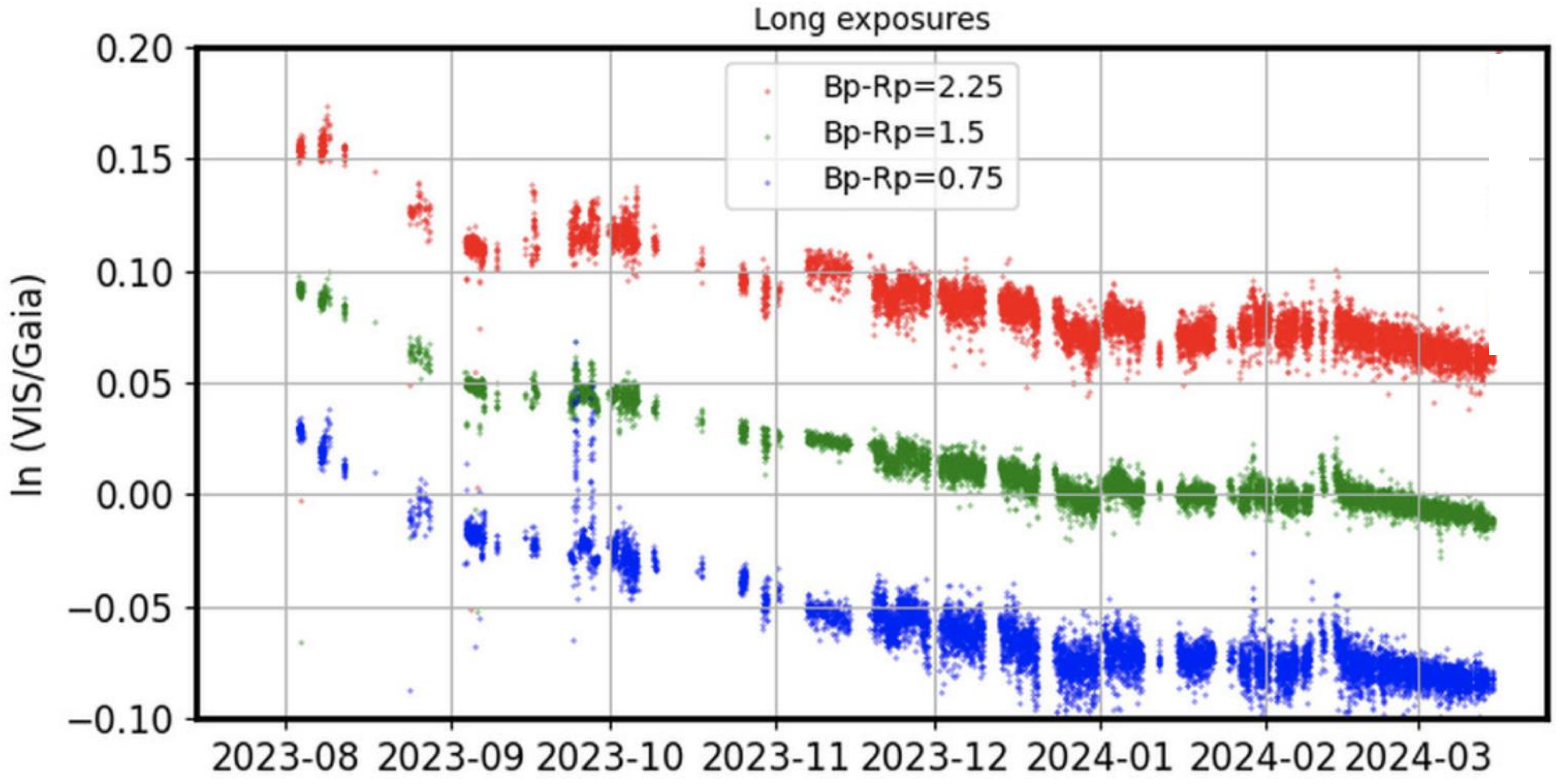


Fine guidance sensor (FGS) tracking anomaly correction

Credit: ESA / Euclid Consortium /NASA / K. Kuijken



The importance of monitoring



ESA / Euclid Consortium / K. Kuijken

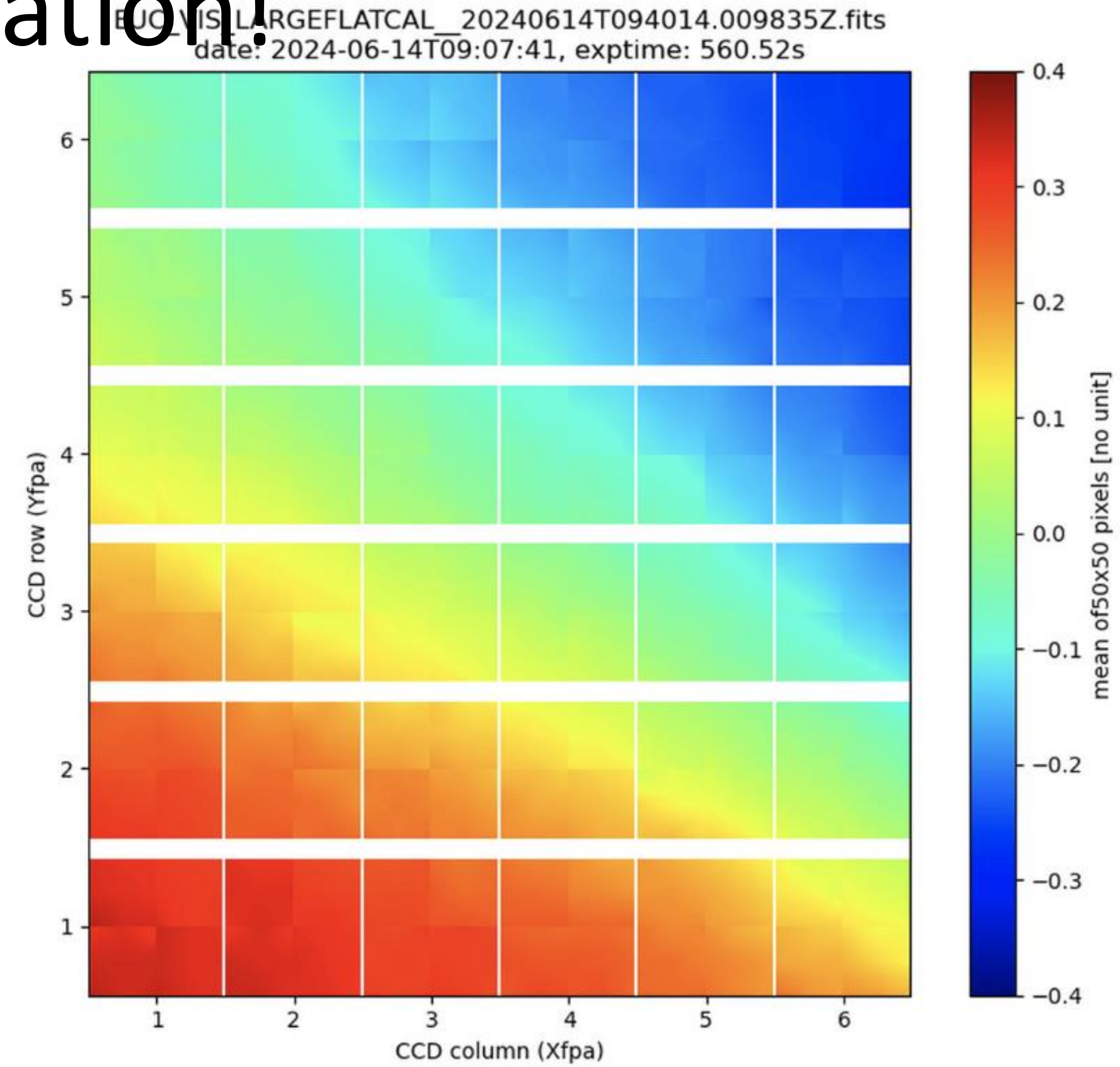
Ice!

- Material outgassing in a vacuum leads to molecular contamination
- a well-known problem in spaceflight
- too much ice means that calibration requirements cannot be met anymore
- Euclid must be thermally decontaminated

Schirmer+2023

MLI layers. *Credit: John Rossie / AerospaceEd.org, CC BY-SA 3.0*

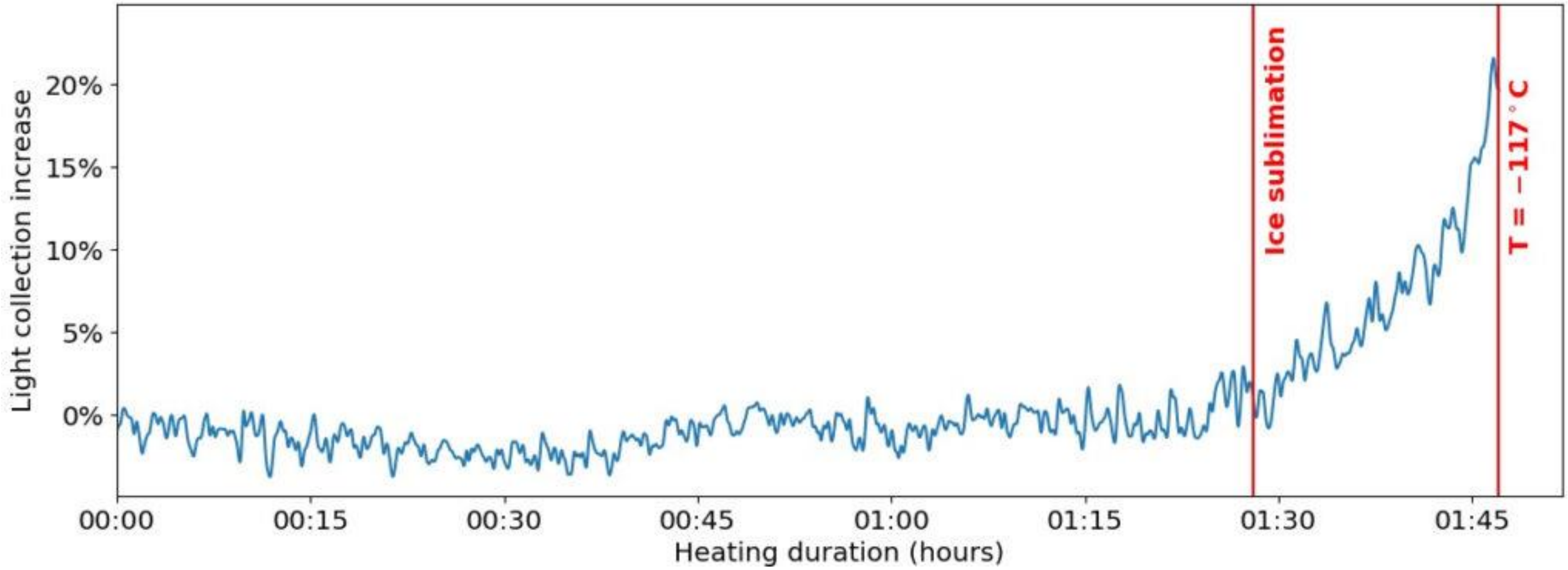
The importance of monitoring: ice contamination!



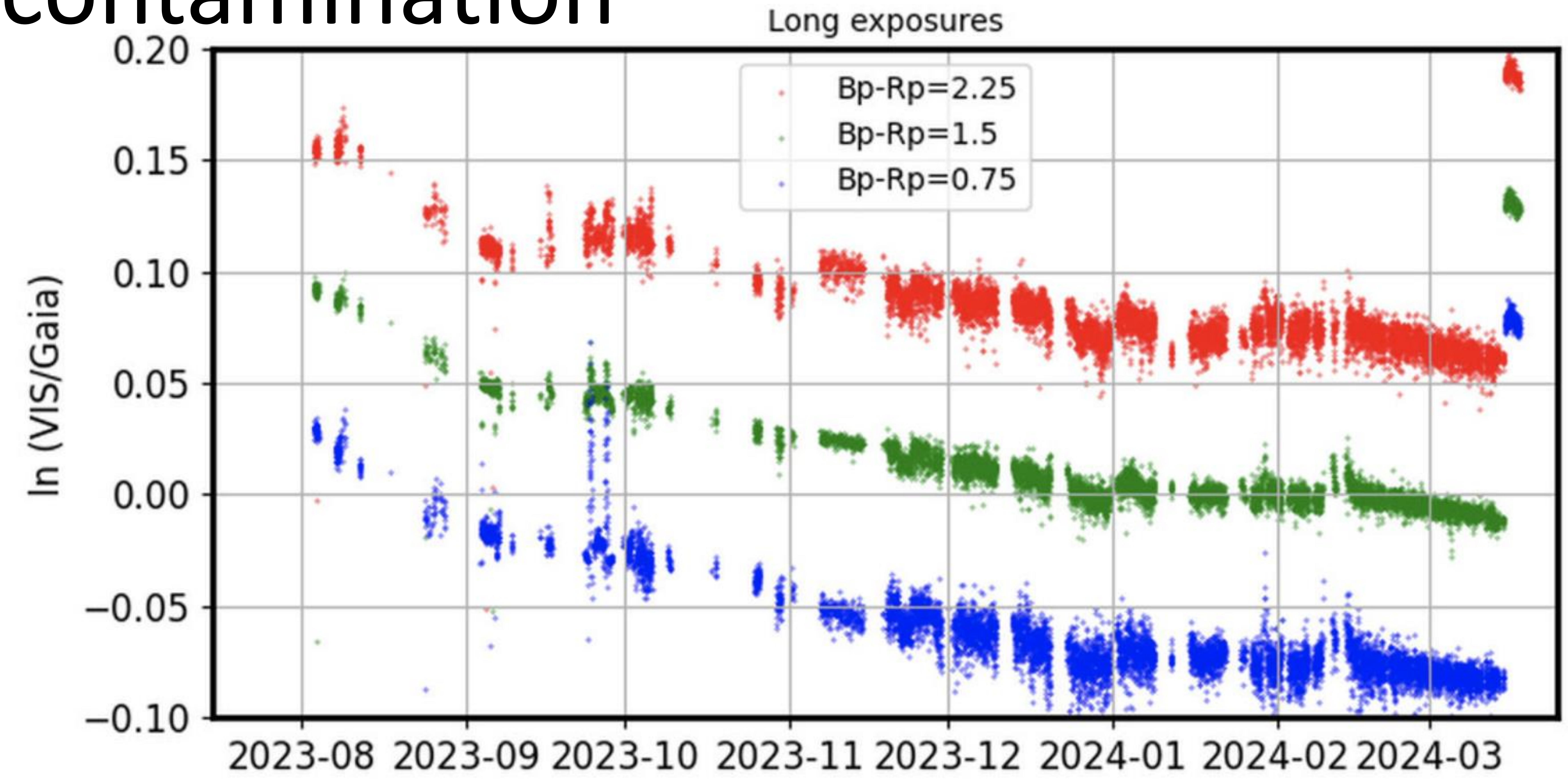
ESA / Euclid Consortium / NASA / EC-SGS

The importance of monitoring: ice decontamination

ESA / Euclid Consortium



The importance of monitoring: ice decontamination



ESA / Euclid Consortium / K. Kuijken

March 2024: first de-icing contamination

June 2024: second de-icing contamination

5. Additional considerations and conclusion

With great statistical power comes big data

Challenges of data downlink, storage, processing and release

- **Euclid:**
  - 9Gb for one VIS frame and associated products (weight map, background map, etc).
  - One single run of MER processing more than 500GB in ~10+hours.
  - Several 10PB over the full surveys

- **Vera Rubin Observatory:** https://rubinobservatory.org/for-scientists/rubin-101/key-numbers
  - Each image is 8Gb. 1000 per night + 450 calibration exposures
  - 20 TB per night. 60 PB over 10 years. Several hundreds PB after processing
  - Prompt processing is required to raise alerts (in case of transients): ~10millions per night

The need for complementary observations

Lower Priority to Higher Priority

Complementary Data
- necessary for core Euclid cosmology measurements
- examples:
    - multiband optical imaging (wide field and deep/calibration fields)
    - spectroscopy for photometric redshift (photo-z) calibration
    - stellar spectroscopy for PSF modelling
    - HST imaging for galaxy shape calibration

Enhancing Data
- enhance Euclid cosmology measurements, but not required
- examples: infrared imaging of deep + calibration fields

Ancillary Data
- enables broad legacy science

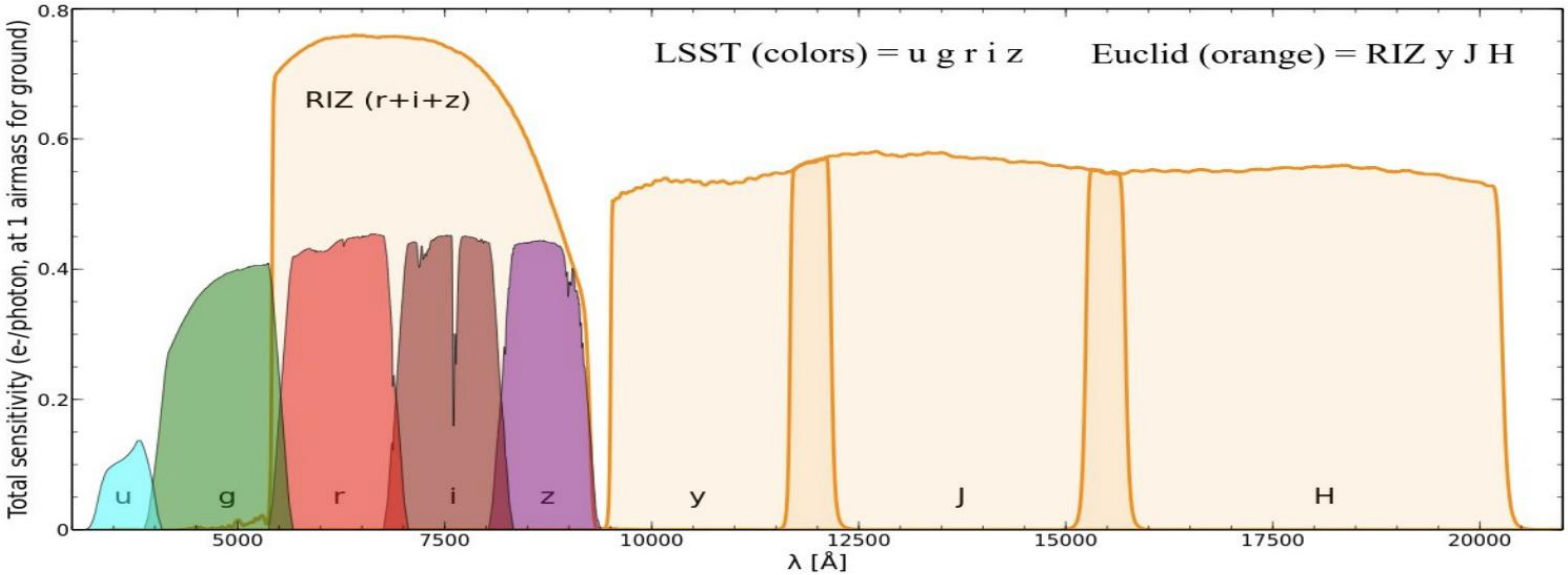
Tertiary Data
- enables specific legacy science

Complementary Observations Group: J.C. Cuillandre (wide survey), D. Stern (deep survey & spectroscopy) and K. Kuijken (end-2-end)

Aim: coordinate, prioritize, and track efforts to obtain complementary observations for Euclid

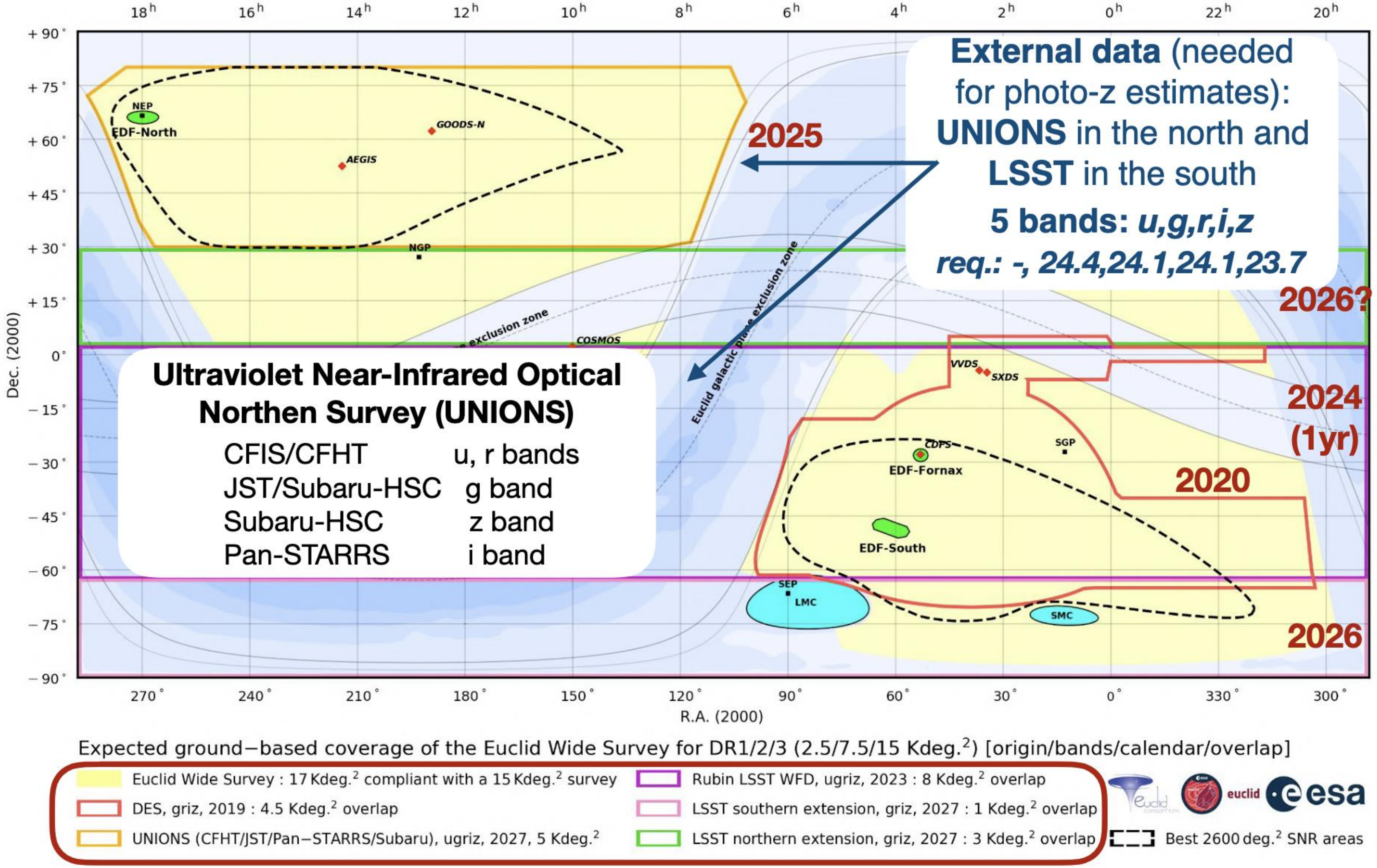
from D. Stern presentation, Euclid Meeting 2021

The importance of synergies between surveys



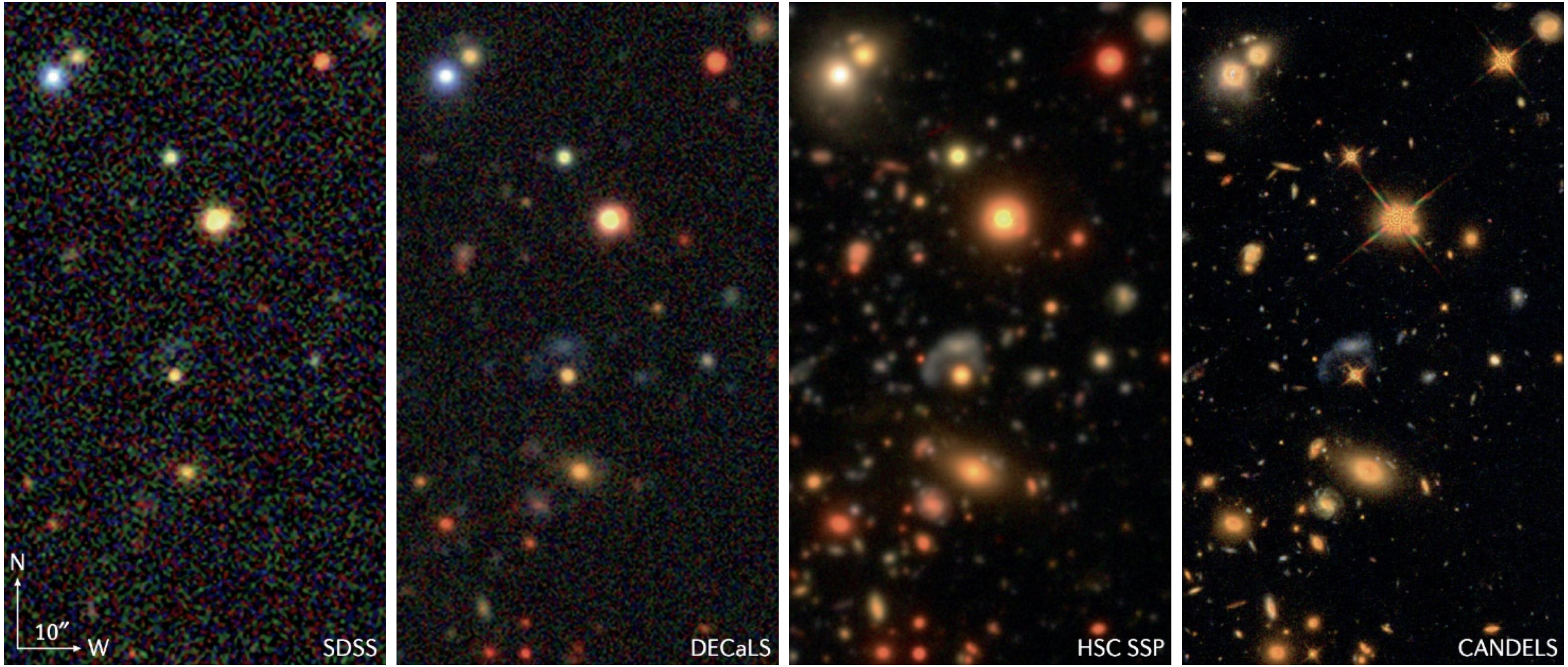
The importance of synergies between surveys

+GAIA



The importance of synergies between surveys: deblending

Melchior, P+2021



Conclusion

- **Data acquisition challenges:**
  - Meeting the aimed precision for cosmology requires drastic calibrations and pixel-level corrections
- **Other challenges that I didn't talk much about**
  - Complementary probes and synergies are pivotal to make a survey give its best
  - How to get from the images to galaxy catalogues (source extraction, profile fitting, photometric redshifts)
  - The amount of data poses new challenges in terms of storage and processing
  - Interpretation of the lensing signal is not immune to astrophysical processes (intrinsic alignments, etc.)
- **Your take home message:**
  - Understanding data acquisition is pivotal to control systematics
  - It drives you closer to the physical reality of the experiment, and it is actually fun!
- **NB: many other probes and telescopes not discussed today**: PSF, WST, CSST, MUST, Lyman-alpha forest, radio, etc.